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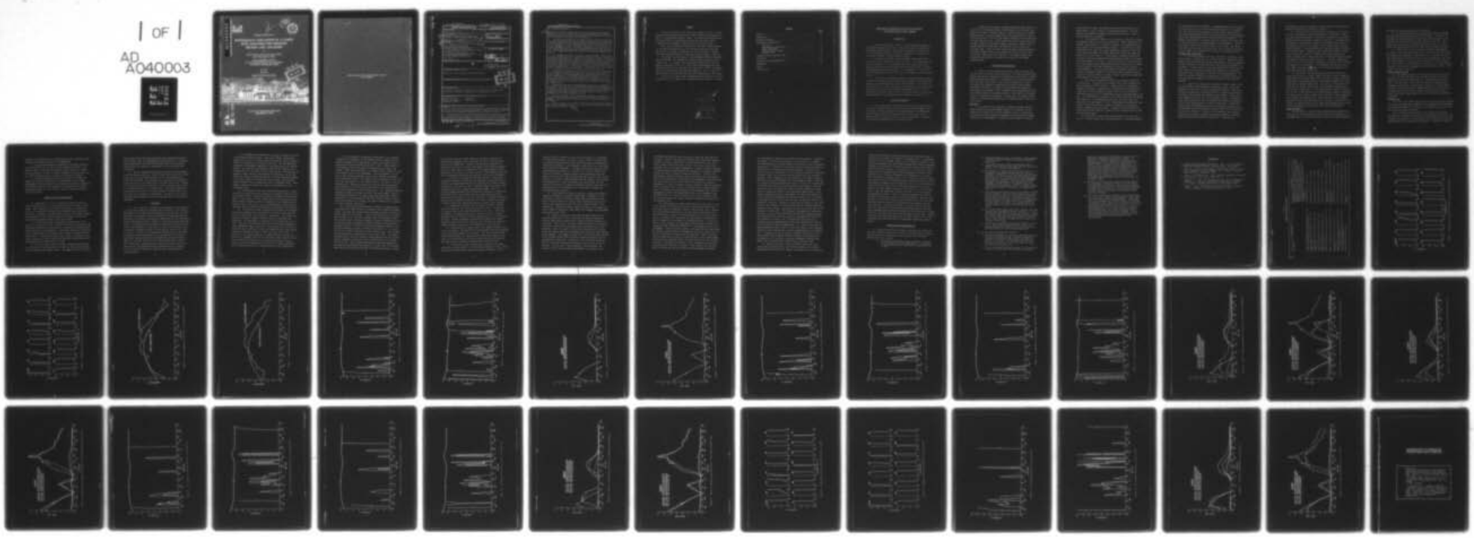

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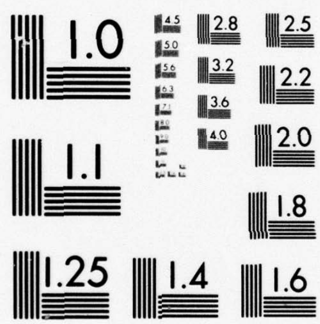

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TECHNICAL REPORT Y-77-3

WATER-QUALITY EVALUATION OF A LOWER POOL ELEVATION FOR PROPOSED ARCADIA LAKE, OKLAHOMA

by

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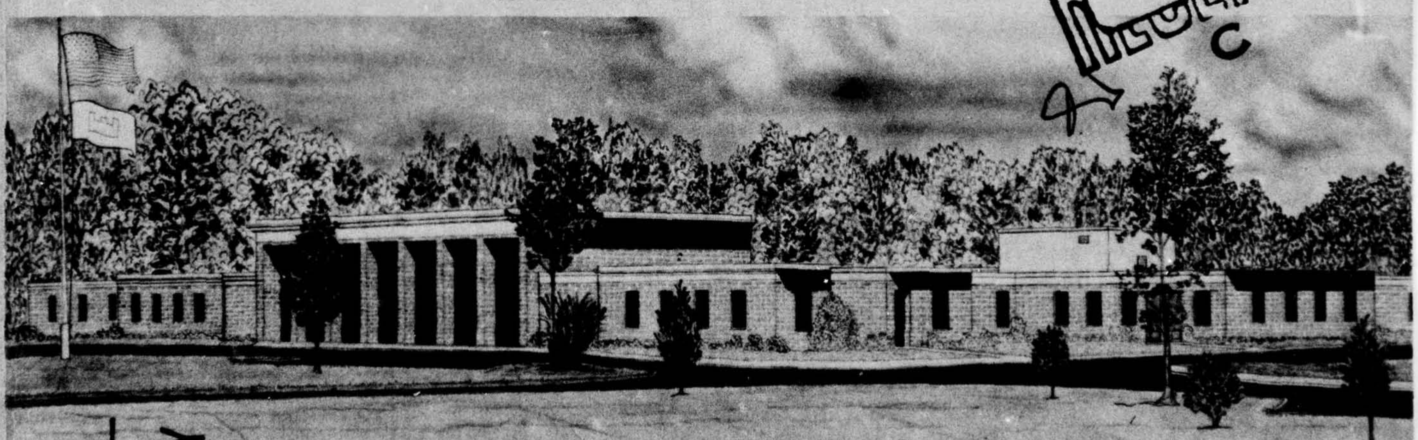
Final Report



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This report is intended to supplement the principal report, "Arcadia Lake Water-Quality Evaluation," conducted at pool elevation, 311 m msl.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study evaluated the water quality of the proposed Arcadia Lake at the lower pool elevation, 305 m msl, and supplemented the principal report, "Arcadia Lake Water-Quality Evaluation," conducted at pool elevation 311 m msl.

The water quality of the proposed Arcadia Lake at the lower pool elevation was investigated using a version of the reservoir portion of the Water Quality for River-Reservoir Systems (WQRRS) ecological model. Although other water-quality constituents were simulated, the study concentrated on (Continued)

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temperature, dissolved oxygen, algae, and coliform bacteria concentrations. Chemical and biological model coefficients and meteorological, streamflow, physical, chemical, and biological model updates for study years 1970 and 1973 were identical to those used in the principal study.

The reservoir was predicted to thermally stratify intermittently during the spring and summer months, but in general was isothermal at the lower pool elevation. Wind mixing was a dominant factor affecting the thermal structure of the impoundment. The isothermal conditions in the reservoir resulted in release temperatures similar to reservoir temperatures. In general, the release temperatures were lower than target temperatures during the winter and early spring, and higher than target temperatures during the summer and early fall. The release temperatures were within 7°C of the target temperatures, however.

The usually well-mixed pool resulted in dissolved oxygen concentrations generally greater than 5 mg/ℓ. Anoxic conditions did develop in the hypolimnion during brief periods of intermittent stratification, however. The average duration of the stratification periods was approximately 6 days. The aerobic environment should reduce the potential iron and manganese problems predicted in the principal study; but manganese is expected to violate drinking water standards the majority of the time while iron may occasionally exceed standards near the headwater area of the impoundment. The standards for iron and manganese are based on aesthetic rather than toxicological considerations.

Depending upon hydrometeorological conditions, two or three major algae blooms were predicted during the study years. Most blooms are expected to consist primarily of nannophytoplankton with some blooms composed of nearly equal concentrations of netphytoplankton and nannophytoplankton. It is expected these blooms will be similar in magnitude and composition to those occurring in Lakes Keystone, Thunderbird, and Carl Blackwell and may cause taste and odor problems in the water supply if not considered in water supply treatment design.

EPA criteria and State of Oklahoma primary body contact standards for fecal coliform bacteria were not violated near the dam at any time during the simulations. Coliforms are expected to exceed standards in the headwater area of the impoundment and, at times, may be high in the upper third of the impoundment. During major storm events (2-5 day hydraulic residence time), standards may be violated throughout the pool.

Considering available data, environmental chemistry, and analytical precision, pesticides and heavy metals are not anticipated to vitiate project purposes. Additional data collection for mercury and heptachlor epoxide is recommended.

Project purposes of flood control, municipal and industrial water supply, and general recreation are expected to be met by the predicted water quality for the proposed Arcadia Lake.

<u>Preface</u>

The work described in this report was performed by the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the U. S. Army Engineer District, Tulsa. The project was authorized by Intra-Army Order for Reimbursable Services No. DOL 740015, dated 2 August 1974 and amended 31 August 1976 for the present study.

This report describes an evaluation of the water quality expected in the proposed Arcadia Lake at the lower pool elevation, 305 m msl. This report is intended to supplement the principal report, "Arcadia Lake Water-Quality Evaluation," conducted at pool elevation, 311 m msl.

The project was undertaken by the Environmental Effects Laboratory (EEL) at the WES. The research was conducted under the direct supervision of Mr. D. L. Robey, Chief, Ecosystem Modeling Branch, and the general supervision of Drs. R. L. Eley, Chief, Ecosystem Research and Simulation Division, and John Harrison, Chief, EEL. Drs. K. W. Thornton and D. E. Ford served as principal investigators. Mr. R. R. Hall, Jr., participated in the study and assisted in the preparation of this report.

Director of the WES during the preparation and publication of this report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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WATER-QUALITY EVALUATION OF A LOWER POOL ELEVATION FOR PROPOSED ARCADIA LAKE, OKLAHOMA

Introduction

1. This report presents results of a water-quality evaluation of the proposed Arcadia Lake at pool el 305 m msl based on mathematical ecological modeling studies. This report was prepared to provide the U. S. Army Engineer District, Tulsa, with guidance on the impact of a lower pool elevation on reservoir water quality.

2. Another more intensive study, "Arcadia Lake Water-Quality Evaluation,"[1] was conducted at pool el 311 m msl. This study supplements the other analyses. It is recommended that the "Arcadia Lake Water-Quality Evaluation" report be consulted for specific details concerning the mathematical modeling approach. For the remainder of this report, the study conducted at pool el 311 m will be referred to as the principal study.

3. The project as authorized includes a multiple-purpose reservoir located on the Deep Fork River near Arcadia, Oklahoma, for flood control, municipal and industrial water supply, and recreation. The project, as formulated for this study, would have a conservation pool 17 m deep near the dam at el 305 m and would impound approximately 3.4×10^7 m^3 of water having a surface area of 736 ha. This would create a lake extending approximately 9 km upstream from the dam with a mean depth of 4 m.

Simulation Approach

4. The water-quality simulations were conducted using an improved version of the Water Quality for River-Reservoir Systems (WQRRS) reservoir model. Several modifications and improvements in the WQRRS model have been made since it was first applied to Arcadia Lake in 1975. Results should be analyzed in terms of relative increases or decreases in magnitude and phasing and not in absolute terms.

5. Chemical and biological modeling coefficients were identical to those used in the principal study. Modifications to the physical components of the model required changes in several physical coefficients. Simulations were conducted using inflows previously modified to represent the diversion of the Northside Sewage Treatment Plant effluent from the upper Deep Fork River. Model simulations used the same daily meteorological updates and monthly streamflow, physical, chemical, and biological updates for study years 1970 and 1973 as were used in the principal study. These two years represented below- and above-average flow years, respectively, for the period from 1969 to 1974 for which stream water quality data were available. The chemical updates had previously been modified to consider the diversion of the sewage treatment plant.

Water-Quality Simulations

6. Table 1 lists a series of simulations, and their objectives, that were run on the 1970 and 1973 data sets. The data from these simulations were used to investigate the sensitivity of the model to various modeling coefficients (Table 1). Since there is some error associated with each model coefficient or rate constant similar to the errors associated with sampling or measuring river inflows (model updates), the model's sensitivity to changes in coefficients and updates was investigated to determine if this variability would significantly affect conclusions drawn from the modeling results. The results are discussed below for the following conditions: (a) base case, (b) varying coefficients, (c) varying light penetration, (d) varying nutrient inflow, and (e) el 308 m.

Base case

7. The reservoir was predicted to thermally stratify intermittently during the spring and summer months but, in general, was isothermal at the lower pool elevation (Figures 1 and 2). During both 1970 and 1973, wind mixing was a dominant factor affecting the thermal structure of the impoundment. The reservoir would begin to stratify

during periods of warm, calm weather but would mix during periods of windy weather. This is typical of Oklahoma impoundments. The same pattern of intermittent thermal stratification was found to occur in Keystone Reservoir, Oklahoma.[2]

8. The isothermal conditions in the reservoir resulted in release temperatures similar to reservoir temperatures. Target temperatures for releases were selected to correspond to natural river temperatures and were obtained from long-term monthly averages. In general, the release temperatures were lower than target temperatures during the winter and early spring and higher than target temperatures during the summer and early fall in 1970 (Figure 3). Meteorological conditions during 1973 resulted in reservoir temperatures increasing more slowly in the spring but staying warmer in the fall. This was reflected in release temperatures that lagged target temperatures during the spring and early summer but were greater than target temperatures during the fall and early winter (Figure 4). Because of the generally isothermal conditions, the selective withdrawal capability for meeting release temperature objectives was not fully realized. However, release temperatures always were within about 7°C of target temperatures.

9. The dissolved oxygen (DO) budget was influenced by periods of wind mixing. In general, DO was greater than 5 mg/ℓ throughout the pool during most of 1970 (Figure 5). During periods of intermittent thermal stratification, hypolimnetic DO concentrations decreased below 5 mg/ℓ and, in three instances, reached 0 mg/ℓ in the bottom layers. The average duration of the stratification periods was approximately six days. DO concentrations, in general, were lower during 1973 than during 1970 (Figure 6). DO concentrations were also less than 5 mg/ℓ more often and for longer periods of time. Phytoplankton concentrations were greater in 1973, resulting in a greater DO demand from respiration and the subsequent decay processes. In addition, 1973 had greater inflows than 1970 and, therefore, higher detrital loadings that also used DO during their decay.

10. There were two major algal blooms predicted for 1970 (Figure 7). The first algal bloom consisted primarily of nannophytoplankton

and occurred from April through May. Nannophytoplankton were considered to be less than 63 μm in size and would pass through a No. 20 plankton net. The second bloom was composed of nearly equal concentrations of net- and nannophytoplankton and lasted from early July through September. Three major phytoplankton blooms occurred during 1973 (Figure 8). In general, the magnitude of the algal blooms was greater during 1973 than in 1970 and all blooms consisted primarily of nannoplankton. The first bloom began in March and continued until the end of May. The second bloom occurred from early June to mid-July, while the third bloom began in early August and continued until the end of the simulation period.

Varying model coefficients

11. The values specified for each coefficient, in general, represented a mean or average value for the rate process. These values were obtained from the literature, personal experience, or personal communication with authorities on that particular rate process in Oklahoma impoundments. Because there was a variance associated with each coefficient, a series of sensitivity analyses were conducted on coefficients affecting a major compartment of interest such as phytoplankton. The sensitivity analyses permitted an assessment of how water quality conclusions might have changed if different coefficient values had been selected.

12. Sensitivity analyses were conducted on Algae 1 light, nitrogen and phosphorus half-saturation coefficients, Algae 2 light half-saturation coefficient, and the self-shading coefficient. None of the coefficient changes had a significant effect on thermal stratification. In addition, the nitrogen and phosphorus half-saturation coefficients had no apparent effect on any of the simulation results. Changing the light half-saturation and the self-shading coefficients had minimal effect on the DO concentrations for the two study years. During 1970, varying light half-saturation coefficients resulted in slightly lower DO concentrations during mid-May but slightly greater DO concentrations in early July (Figure 9). Overall, the DO budget was quite similar. During 1973, the annual DO budget was slightly greater by varying the light half-saturation coefficient (Figure 10). Increasing the

self-shading coefficient resulted in slightly higher DO concentrations during both 1970 and 1973 (Figures 11 and 12).

13. Varying the light half-saturation coefficient had a significant effect on predicted algae concentrations. During 1970, varying the algae light half-saturation coefficients resulted in the net phytoplankton becoming the dominant community (Figure 13). The spring bloom was composed of approximately two-thirds net plankton and one-third nannoplankton, while the late summer bloom consisted almost entirely of net phytoplankton. The phytoplankton also maintained higher concentrations between blooms. Varying the algae light half-saturation coefficients during 1973 resulted in slightly lower blooms during early spring and summer with a significant shift in dominance within the plankton community during late summer (Figure 14). The late summer bloom consisted of an initial peak of net plankton followed by a bloom of similar magnitude of nannoplankton. The magnitude and duration of this late summer bloom was significantly less following the change in the light half-saturation coefficients.

14. During 1970, the self-shading coefficient resulted in a lower spring bloom but a higher summer bloom than the base (Figure 15). Light limited the increase during the first bloom. However, during the second bloom, zooplankton grazing on the plankton community was lower, resulting in a greater summer bloom. Since the first bloom was not as large with the greater self-shading, the zooplankton population did not increase in magnitude as it did during the base case and initially was not able to graze as much on the phytoplankton community during June. The second bloom, therefore, began earlier and was of greater magnitude at the higher self-shading value. Solar radiation was also greater during the second bloom than during the first bloom. During 1973, the blooms were delayed slightly at the higher self-shading values but were similar in magnitude to the blooms in the base case (Figure 16).

Light penetration

15. The effect of increased and decreased light penetration on water quality was investigated by varying the Secchi disk depth. In the WQRRS model, the Secchi disk depth is used as a relative measure for

the depth of light penetration into the reservoir.

16. The Secchi disk depth had no significant effect on thermal stratification and minimal effects on the DO budget. In general, the DO budget was slightly greater at the lower Secchi disk value of 1 m than the base case for both study years (Figures 17 and 18). The DO budgets for the base case and higher Secchi disk values of 3 m were similar throughout the year for both 1970 and 1973 (Figures 19 and 20).

17. During 1970, the first bloom was delayed by approximately one month at the lower Secchi disk value of 1 m, while the second bloom was delayed by approximately 15 days (Figure 21). Although the second bloom was delayed at the Secchi disk of 1 m, the magnitude of the bloom was slightly greater. The first bloom was less at the Secchi disk of 1 m. During 1973, all algae blooms at a Secchi disk of 1 m were delayed slightly in starting but the magnitude of the blooms was similar for all Secchi disk values (Figure 22).

Varying nutrient inflow

18. The simulated update nutrient concentrations (NH_3-N, NO_3-N, and PO_4-P) flowing into Arcadia were doubled and halved to evaluate their impact on reservoir water quality. The algae blooms were identical to the base case. Since light was limiting the phytoplankton assemblage, doubling the nutrients had no effect on the phytoplankton. It appears that advanced waste treatment would have to reduce nutrient concentrations much lower than 50 percent of their present values before any apparent changes might occur in the reservoir phytoplankton assemblage.

Elevation 308

19. Since some quality constituents in the present study increased while others decreased when compared to the principal study, simulations were therefore conducted to determine if an intermediate elevation would have ameliorated these conditions.

20. The thermal stratification at the higher pool elevation was similar to the base case for 1970 and 1973 (Figures 23 and 24). The reservoir was predicted to intermittently stratify during the spring and summer months but, in general, was isothermal. Although the reservoir

elevation was increased by 3 m, wind mixing was still a dominant factor affecting the thermal structure of the impoundment.

21. The DO concentrations were greater at the higher elevation than the base case for both 1970 and 1973 (Figures 25 and 26). The greater volume of water and the frequent mixing resulted in a larger DO mass available to satisfy a similar DO demand to the base case. The net result, therefore, was an increase in the overall DO budget.

22. The spring plankton blooms were similar at the lower and higher pool elevation during 1970, but the magnitude of the summer nannoplankton bloom was greater at the higher pool elevation (Figure 27). The plankton blooms were all diminished at the higher pool elevation during 1973 (Figure 28). The timing of the three blooms was similar at both elevations.

Comparison with Principal Study

23. Simulations at el 311 m indicated the reservoir would be weakly stratified from mid to late spring through late summer or early autumn. The intermittent stratification predicted at the lower pool el, 305 m, was expected considering the relatively high average wind velocities in Oklahoma. Although complete mixing in the summer occurred less frequently in the principal study, stratification also was disrupted during extended periods of high wind velocity.

24. Intermittent rather than prolonged stratification at the lower pool elevation did result in higher DO than in the principal study. Wind mixing continuously replenished the DO depleted by respiration and decay processes in the hypolimnion. During brief periods of stratification, the hypolimnetic DO decreased and, at times, the hypolimnion did become anoxic. During the principal study, however, prolonged stratification occurred, a greater volume of the hypolimnion became anoxic, and anoxia persisted for longer periods of time.

25. The first algae bloom was similar in magnitude and duration to the bloom in the principal study for 1970, but the second bloom was lower in magnitude and slightly longer. The magnitude of the first and

third blooms during 1973 was nearly double the concentration found in the principal study. Net phytoplankton contributed more to the second bloom during 1970 at the lower pool elevation than in the principal study but was very similar in concentration to the principal study during 1973.

26. State of Oklahoma water-quality standards and Environmental Protection Agency criteria for fecal coliform bacteria were not violated at any time or at any depth during the 1970 or 1973 simulations at either pool elevation. The simulations are considered most representative of the area in the deepest part of the pool near the dam. Simulation results should not be interpreted to mean violations may not occur in the headwater areas or in isolated coves. Violations during major storm events (storms with 2- to 5-day hydraulic residence times in the pool) may occur throughout the impoundment. During most storm events, violations may be expected to occur in the upper third of the proposed impoundment.

Discussion

27. It is important to realize that mathematical ecosystem models are in the early stages of development and verification. The original documentation of the WRE model was published by Chen and Orlob in 1972.[3] During the succeeding five years, there have been significant improvements made to the model, but neither the WQRRS model nor any other mathematical water-quality model is capable of predicting so-called "absolute values." Preliminary research evaluations indicate that predictive values for some parameters at times may be in error by more than an order of magnitude of measured values or by two weeks of the onset of a specific event. However, if the assumptions and limitations of the model are understood and incorporated in the interpretation of the output, the general response predicted by the model will provide valuable insight into the water quality of the proposed Arcadia Lake. Despite their limitations, existing modeling techniques properly used in conjunction with other appropriate study approaches may be considered as one of the more reliable and versatile tools for making water-quality analyses.

28. The WQRRS model assumes that a reservoir consists of a series of well-mixed horizontal layers. Thus, while spatial concentration gradients in the vertical direction can be evaluated, spatial gradients cannot be evaluated in the horizontal direction. The one-dimensional assumption of the WQRRS is important in the interpretation of modeling results. The predicted water-quality conditions are considered most representative for the part of the pool near the dam. This area has the greatest volume, the most representative stratification, and the most significant impact on downstream releases. The one-dimensional assumption, however, implies that the model cannot predict isolated water-quality conditions in the headwaters, coves, or embayment areas. These shallow, usually well-mixed areas cannot be represented by a one-dimensional model.

29. The simulations also are considered representative of conditions six to eight years after filling of the reservoir when it is in a less transient state. Transient biological and chemical conditions are known to occur during the first several years after reservoir filling. These transient conditions were not considered in the simulations conducted as part of this study. With an understanding of these basic assumptions, various predicted water-quality conditions can be discussed.

30. The predicted release temperatures and thermal stratification profiles are probably quite representative of actual values that will occur in Arcadia Lake if the project is constructed. The thermal predictions are based on physical processes that are reasonably well understood. The impoundment is predicted to be intermittently stratified. Therefore, the temperature structure will be highly dependent on local hydrometeorological conditions. The intermittent stratification would also make it difficult to meet the average natural stream release temperature objectives during the summer and early fall months. In contrast, at the higher elevation, the summer stratification was predicted to be somewhat stable and the downstream release objectives could be met through the operation of the selective withdrawal structure. However, even during intermittent stratification, release temperatures can be maintained within 7°C of average natural stream temperatures.

31. The seasonal DO concentrations predicted for the proposed Arcadia Lake are dependent on the thermal structure, mixing, and the phasing and magnitude of algal blooms. While no prolonged periods of stratification were predicted during 1970 or 1973, a stable period of stratification could occur during a prolonged period of warm, calm weather. Under these conditions it is probable that DO would go to zero in the deeper strata of the impoundment. Bottom withdrawal, in comparison with surface withdrawal, would be more effective in keeping DO concentrations higher in the deeper strata by withdrawal of the low DO water and replacement of it with higher DO water from above or from inflowing waters. Reaeration through the structure and stilling basin would result in 80 to 95 percent DO saturation of the release waters even during withdrawal of anoxic bottom waters. This represents physical reaeration, however, that may not satisfy the oxygen demand in the release waters, resulting in an oxygen sag farther downstream. Based on an analysis of DO data downstream from other Oklahoma reservoirs when anoxic bottom waters were released, the oxygen sag would not be expected to violate stream DO objectives.[2]

32. As indicated by the sensitivity analyses and light penetration simulations, light would be an important factor regulating plankton growth. The lower pool elevation with the smaller volume is expected to be more turbid for two reasons. First, wind mixing will have a greater mixing effect at the lower pool elevation than in the previous study. This should result in a greater suspension of matter throughout the water column and possible resuspension of bottom particles during periods of high wind velocity.[4] Second, the theoretical hydraulic residence time has been decreased by nearly one third in both years (3.2 to 1.2 years and 1.6 to 0.5 years during 1970 and 1973, respectively). The residence time during 1973 is now predicted to be less than 1 year. The higher flushing rates at the lower elevation should generally result in greater in-pool turbulence, which would tend to suspend particles for longer periods of time. This increased turbidity may reduce the magnitude of the predicted phytoplankton populations but it may result in coliforms, heavy metals, and pesticides adsorbed onto sediment particles to remain

in the water column for longer periods of time before settling out. Turbidity and suspended solids concentrations are not currently simulated with the WQRRS model. However, the sensitivity analyses does indicate there would be a fairly large range of algal responses depending on the light regime. The magnitude of the phytoplankton blooms is expected to be on the order of that occurring in many Oklahoma reservoirs such as Thunderbird Lake, Keystone Reservoir, and Lake Carl Blackwell.

33. Doubling or halving the inflowing nutrient concentrations or varying the nitrogen or phosphorus half-saturation coefficients did not influence the phytoplankton because the inflowing and in-lake nutrient concentrations were over an order of magnitude higher than those levels considered necessary to support phytoplankton growth. Since the Northside Sewage Treatment Plant effluent was considered to be diverted outside the basin, the nutrients are those resulting from nonpoint sources that are difficult to control and reduce. The model simulations indicated that substantial reductions in nutrient concentrations would be required before any significant decrease in algae blooms occurred.

34. Simulations indicate that the reservoir would be intermittently stratified at the lower pool elevation of 305 m. In general, DO concentrations would be greater than at pool el 311 m. The aerobic environment in the hypolimnion should reduce the level of iron and manganese near the dam below the level predicted to occur in the principal study. However, manganese concentrations probably would exceed standards the majority of the time while iron only would be expected to exceed standards occasionally in the headwaters of the reservoir.

35. During periods of algal blooms, water supply treatment costs could be increased. The magnitude of the 1973 algal bloom could diminish the recreational potential of the project. The other simulated algae blooms would probably not interfere with recreational purposes of the lake to any extent greater than that occurring in other nutrient-rich Oklahoma reservoirs presently receiving heavy recreational use.

36. The principal study indicated pesticides and other heavy metals were not anticipated to vitiate project purposes of flood control, municipal and domestic water supply, and general recreation. While

results from this study do not alter this conclusion, it is important to realize this conclusion is based, in part, on EPA's restricted use of potential problem pesticides and their adsorption and sedimentation with particulate matter as the suspended solids settle out in the headwater area of the impoundment. Although turbidity and suspended solids concentrations are expected to be greater in the water column at the lower pool elevation, sampling studies on Lake Thunderbird and Lake Eufala in the previous study indicated pesticide and heavy metal concentrations in the water column decreased down the length of the reservoir. The sedimentation of these constituents may occur farther into the reservoir, but based on information presently available pesticides and heavy metals are not anticipated to be water-quality problems for established project purposes.

37. Total dissolved solids are expected to exceed water-quality standards throughout the proposed Arcadia Lake. Standards for this constituent are based on aesthetic rather than toxicological effects. Fecal coliform standards for primary contact recreation were not violated in the simulated area near the dam in either the 1970 or 1973 computations. Standards, however, might be violated in the upper third of the reservoir during most storm events and throughout the impoundment during major storm events.

38. Specific conclusions concerning the water quality of the proposed Arcadia Lake at pool el 305 m msl are based on information obtained from several approaches and a state-of-the-art evaluation of these data. While the use of several approaches provides corroborating evidence for each specific conclusion, these conclusions are not unequivocal. There is a degree of uncertainty associated with each approach and varying degrees of uncertainty associated with each parameter being evaluated. For example, simulations of the thermal regime expected in the proposed Arcadia Lake are based on physical processes that are reasonably well understood. Simulations of the biological processes, however, are based on empirical descriptions that are not as well understood. With the use of loading analyses, algal bioassays, and analysis of data from surrounding impoundments, conclusions on the

eutrophication potential can be made with a relatively high degree of certainty. Based on the hydraulic residence time, sensitivity analyses, and decay processes, conclusions on coliform bacteria are also relatively certain for the area near the dam. This is not true for the headwater area of the proposed impoundment. Sediment transport phenomena are poorly understood and mathematical simulations of sediment transport provide only gross estimates of expected conditions. Particle-size distribution, density differences between inflowing stream and impoundment, inflow entrainment, wind mixing, local morphometric characteristics, and other factors all have an influence on the rate and location of sedimentation. Since coliforms are known to adhere to sediment particles, their distribution will, in part, be dictated by the sediment distribution. As evidenced by delta formation in the headwater areas of most impoundments, much of the sedimentation occurs in the headwater area; therefore, most of the coliform colonies will also be deposited there. The coliform colonies that remain attached to suspended particles die at an exponential rate.

39. While additional pesticide and heavy metal data were not collected during this study, the lower pool elevation may modify some of the conclusions on contaminants stated in the principal study. Because of these potential modifications, the pesticide and heavy metal data were reevaluated in light of conditions expected at the lower pool elevation. The majority of pesticides and heavy metals entering Arcadia Lake are expected to be adsorbed on suspended particles. As with coliforms, in-lake pesticide and heavy metal concentrations are expected to be significantly reduced by sedimentation in the headwater areas of the impoundment. Unlike coliforms, however, some pesticides and heavy metals may undergo complex chemical transformations that may increase the solubility of the constituent under certain conditions. These transformations are affected by a variety of conditions such as pH, oxygen regime, redox potential, chelating agents, and other factors that are difficult to predict. The degree of certainty of the conclusions on pesticides and heavy metals, therefore, is reduced. This reflects both the variance in the data base and the current state-of-knowledge surrounding

the environmental chemistry of pesticides and heavy metals. Pesticides do degrade to innocuous compounds but at various rates. In general, the organophosphorus compounds degrade more rapidly than the chlorinated hydrocarbons. Partially for this reason, EPA has placed restrictions or banned the use of various chlorinated hydrocarbons. Based on these restrictions, the concentrations of the pesticides indicated as potential problems in this report and the principal study report are expected to diminish. This is supported by their reduction in the water columns of Lake Eufala and Lake Thunderbird from the headwaters toward the dam and by a general decreasing concentration trend of several of the pesticides in the Deep Fork River since use restrictions were imposed. The fish collected in the Deep Fork River clearly violated the FDA body burden limit for heptachlor epoxide on that particular sampling date. Since aquatic organisms do depurate contaminants and analytical anomalies do occur in pesticide determinations, additional samples will be required to determine if this violation was the norm, an analytical error, or an improbable occurrence. Heptachlor epoxide was not detected in the water column or the sediments of the Deep Fork River near Arcadia during the principal study. However, heptachlor was found in the water but not the sediments on 22 May 1974. Both heptachlor and heptachlor epoxide were detected in the Deep Fork River during the 1976 ACOG sampling program, but concentrations of both were below the recommended EPA criteria for the protection of aquatic life.[5] While various pesticides can be indicated using gas chromatography, definitive identification requires further analysis using mass spectrometry. It is possible that the compound exceeding the FDA criteria for fish body burden is not heptachlor epoxide but some compound with a similar chromatographic peak residence time. An analysis of fish collected in Oklahoma reservoirs as part of the National Pesticide Survey indicated excessive bioaccumulation of pesticides was not occurring in existing impoundments including Lake Eufala which now receives the runoff from the Deep Fork River.

40. Mercury can exist in various chemical states, has known toxicological characteristics, and has been measured in the Arcadia watershed and Deep Fork River. Mercury concentrations in the Deep Fork

River have been found to exceed the criterion for freshwater aquatic life but do not exceed the criterion for drinking water. Unfortunately, the criterion for freshwater aquatic life is below the detection of the analytical equipment used by the USGS, Oklahoma Public Health Department, Oklahoma State University, and others who have collected water-quality data on the Deep Fork River. The sensitivity of the analytical equipment used by the Oklahoma Public Health Department is properly established to detect mercury concentrations for drinking water criteria. The criterion for freshwater aquatic life is nearly two orders of magnitude lower than that for drinking water and below the detection limit of the analytical equipment used for analyses. The fish collected from the Deep Fork River did not exceed the FDA body burden limit for mercury. However, the same argument applies for mercury as it did for the pesticides. This fish sample may represent the norm or it could represent an improbable occurrence. That is, additional samples might indicate the body burden limit for mercury in fish was exceeded. Mercury concentrations in storm runoff from the Deep Fork Basin above Belle Isle Lake have been found to exceed both drinking water and freshwater aquatic life criteria.[5] Mercury data obtained for storm runoff and under elevated flow conditions in the Deep Fork River near Arcadia by the USGS and the Oklahoma State University probably are more indicative of concentrations to be expected in storm event loadings to Arcadia Lake. However, the storm runoff data from above Belle Isle Lake indicate that the extreme upper Deep Fork Basin may be a potentially significant source of mercury.

Conclusions and Recommendations

41. Based upon the above constraints, the data base existing for this study, and the current state of the art for water-quality analyses, specific conclusions concerning the water quality of the proposed Arcadia Lake are as follows:

- a. The proposed Arcadia Lake would be thermally stratified intermittently during the summer months. No permanent or stable temperature stratification is expected at pool el 305 m.

b. During the summer and early fall months, release temperatures may be about 7°C warmer than natural downstream temperatures.

c. In general, dissolved oxygen concentrations will be greater than 5 mg/ℓ with some anoxic periods during brief periods of intermittent stratification.

d. The aerobic environment should reduce the level of iron and manganese concentrations near the dam. However, manganese is expected to violate drinking water standards the majority of the time while iron may occasionally exceed standards in the headwater area of the impoundment. Total dissolved solids are expected to exceed standards throughout the impoundment. The standards for iron, manganese, and TDS are based on aesthetic rather than toxicological considerations and will not result in major water supply problems if considered in treatment plant design.

e. Pesticides and heavy metals are not anticipated to vitiate project purposes. Fecal coliform standards for primary contact recreation were not violated near the dam at any time during the simulations. Coliforms are expected to exceed standards in the headwater area of the impoundment and may be high in the upper third of the impoundment following most storm events. The standards may be exceeded throughout the reservoir following major storm events.

f. Two or three major algae blooms may be expected each year depending upon hydrometeorological conditions. It is expected these blooms will be similar in magnitude to those occurring in Lakes Keystone, Thunderbird, and Carl Blackwell and may cause taste and odor problems in the water supply. These potential problems can be provided for in treatment plant design.

g. Water-quality requirements for project purposes of flood control, municipal and industrial water supply, and general recreation are expected to be met by the predicted water-quality for the proposed Arcadia Lake.

42. The following recommendations are made:

a. The sampling program for coliforms, pesticides, and heavy metals - particularly mercury - should be maintained throughout the planning, construction, and operation phases of the project. Mercury analyses should be performed by equipment with a detection limit well below EPA criteria for aquatic life.

b. Prior to impoundment additional samples of fish should be collected from the Deep Fork River near the proposed

damsite and analyzed for body burdens of mercury and the pesticides, heptachlor and heptachlor epoxide. If heptachlor or heptachlor epoxide is indicated by gas chromatography to be in significant concentrations, its identity should be verified by mass spectrometry. If the results are confirmed, a more thorough evaluation of its source and potential fate and consequences in the reservoir should be made prior to construction. While present evidence does not justify the delay of advanced engineering and design, the CE should be prepared to delay plans for construction if the results of the recommended sampling program indicate a potentially significant problem.

c. Recreation sites should be located in the lower half of the impoundment to minimize potential coliform problems with body contact recreation. The lower half represents a conservative value since most storm events are expected to impact only the upper third of the proposed impoundment with respect to coliforms violating body contact recreation standards.

d. The selective withdrawal capability should be maintained in the structure to permit the withdrawal of water supply from three depths within the impoundments. These three ports should probably be located to permit the withdrawal of epilimnetic water (center line 12 m above the bottom), metalimnetic water (center line 8 m above the bottom), and hypolimnetic water (center line 4 m above the bottom). The hypolimnetic port is in addition to the floodgates. During algae blooms, water may be withdrawn from the bottom to ameliorate taste and odor problems. During stratification periods, surface or metalimnetic waters may be withdrawn to minimize manganese and iron concentrations.

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3. Chen, C. W. and Orlob, G. T. 1972. Ecologic simulation for aquatic environments. Final report OWRR C-2044.

4. Norton, J. L. 1968. The distribution, character, and abundance of sediments in a 3000-acre impoundment in Payne County, Oklahoma. M. S. Thesis. Oklahoma State University, Stillwater, Okla.

5. Carter, P. 1977. Memorandum from City-County Health Department to ACOG. Explanation of Enclosed 208 Data. 17 Jan.

Table 1

Summary of the Simulation Runs

Run No.	Modifications	Objective
1	Base condition	Establish base conditions. Secchi disk = 2.0 m. Settling velocity: ALG 1 = 0.15 m/day, ALG 2 = 0.15 m/day. Growth rate: ALG 1 = 2.0/day, ALG 2 = 1.8/day. Half-saturation coefficients: ALG 1 = 0.003 kcal/m^2-sec light, ALG 2 = 0.005 kcal/m^2-sec light; ALG 1 = 0.10 mg/ℓ N and 0.03 mg/ℓ PO_4-P, ALG 2 = 0.15 mg/ℓ N and 0.06 mg/ℓ PO_4-P. Self-shading coefficient = 0.25/mg/ℓ/m
2	Changed light half-saturation coefficient of ALG 1 from 0.003 to 0.006 and ALG 2 from 0.005 to 0.003	Determine sensitivity of algae to light
3	Changed N half-saturation coefficient of ALG 1 from 0.10 to 0.20	Determine sensitivity of ALG 1 to nitrogen
4	Changed N half-saturation coefficient of ALG 1 from 0.10 to 0.05	Determine sensitivity of ALG 1 to mitrogen
5	Changed PO_4-P half-saturation coefficient of ALG 1 from 0.03 to 0.06	Determine sensitivity of ALG 1 to phosphorus
6	Changed PO_4-P half-saturation coefficient of ALG 1 from 0.03 to 0.015	Determine sensitivity of ALG 1 to phosphorus
7	Changed the maximum Secchi disk depth from 2.0 to 1.0 m	Determine the effect of light penetration on impoundment water quality
8	Changed the maximum Secchi disk depth from 2.0 to 3.0 m	Determine the effect of light penetration on impoundment water quality
9	Changed the self-shading coefficient from 0.25 to 0.50/mg/ℓ/m	Investigate seasonal variations in light extinction
10	Changed inflowing nutrient concentrations by a factor of 0.5 times base concentration	Determine impact of nutrient concentrations on algae
11	Changed inflowing nutrient concentrations by a factor of 2.0 times base concentration	Determine impact of nutrient concentrations on algae
12	Changed elevation from 305 to 308 m	Determine the effect of pool elevation on reservoir water quality

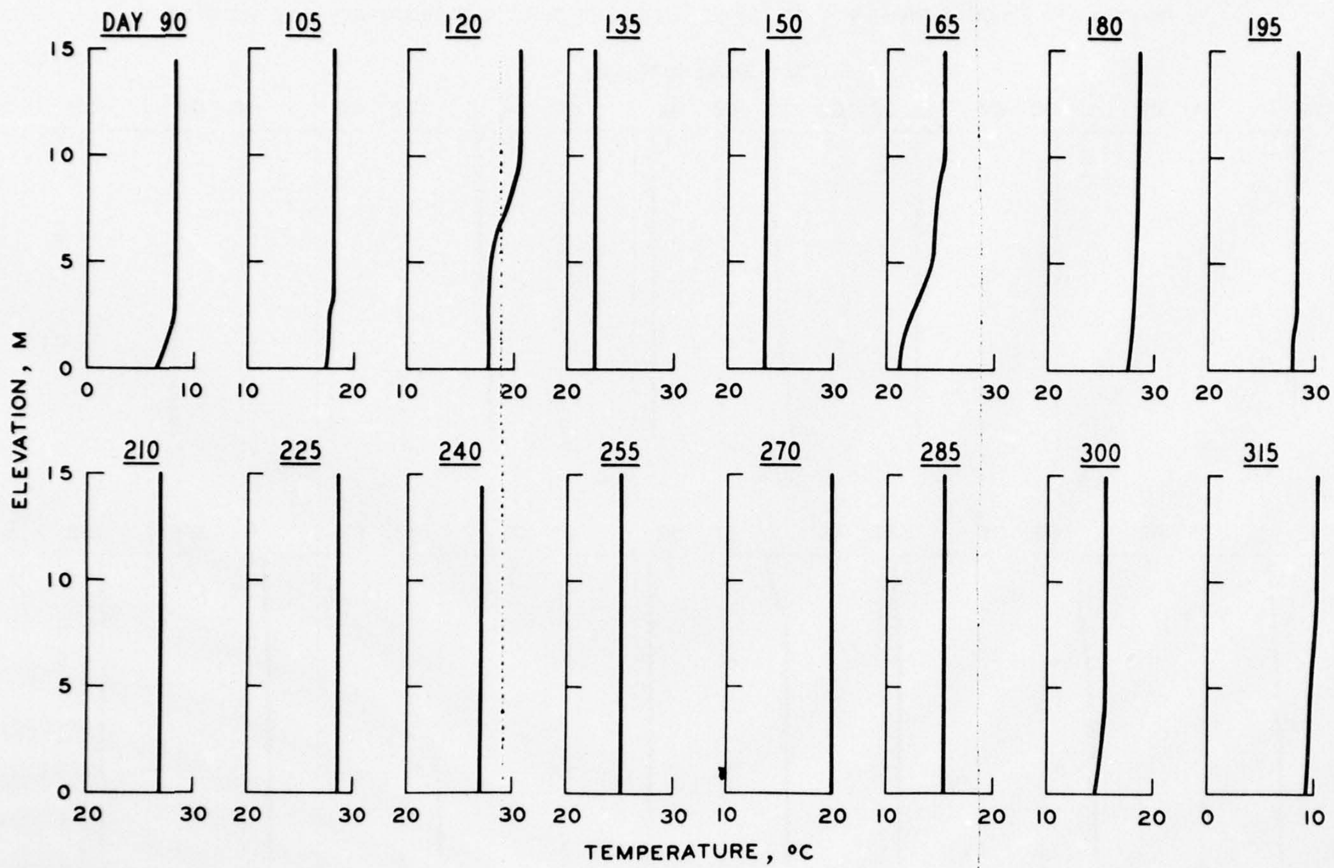

Figure 1. Temperature profiles for 1970 at the lower pool elevation

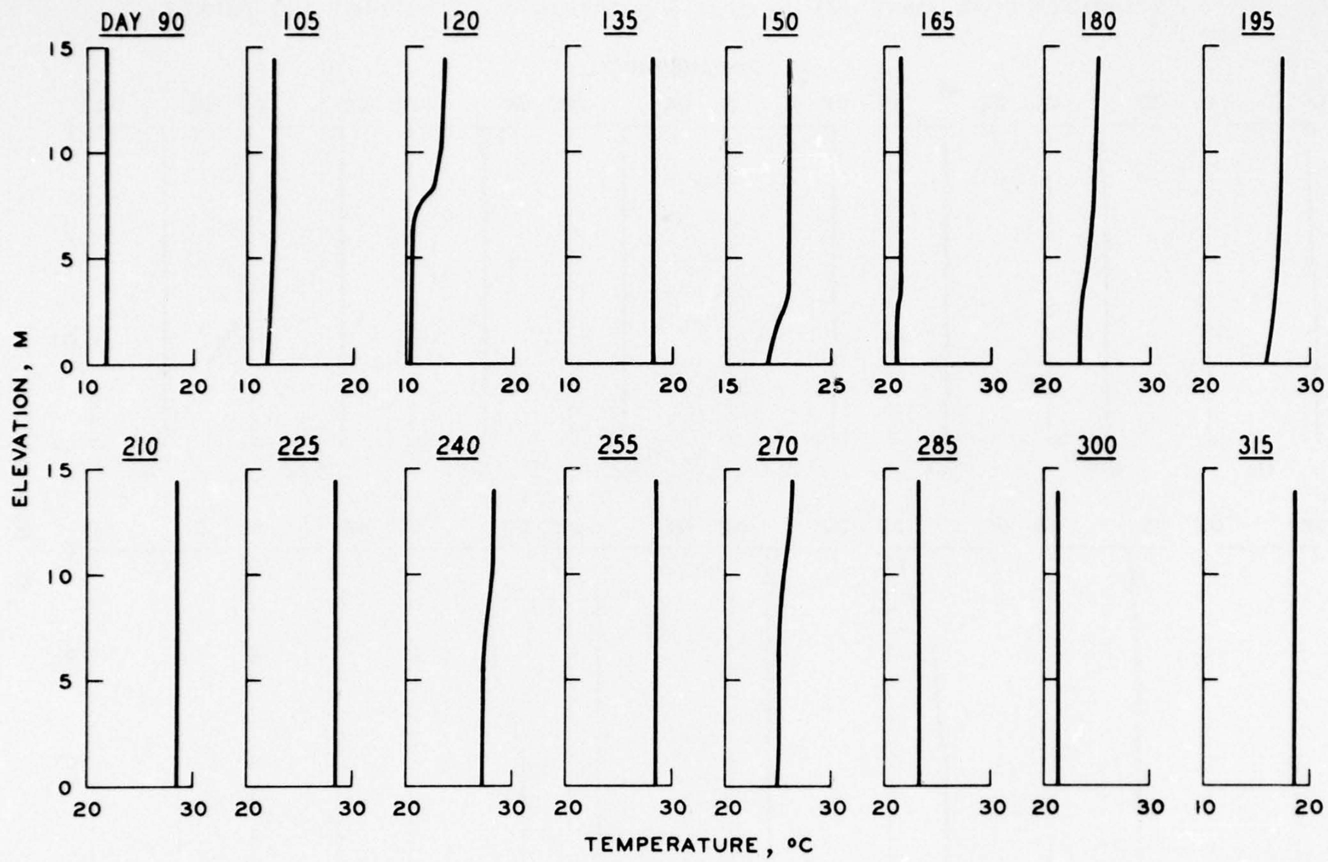

Figure 2. Temperature profiles for 1973 at the lower pool elevation

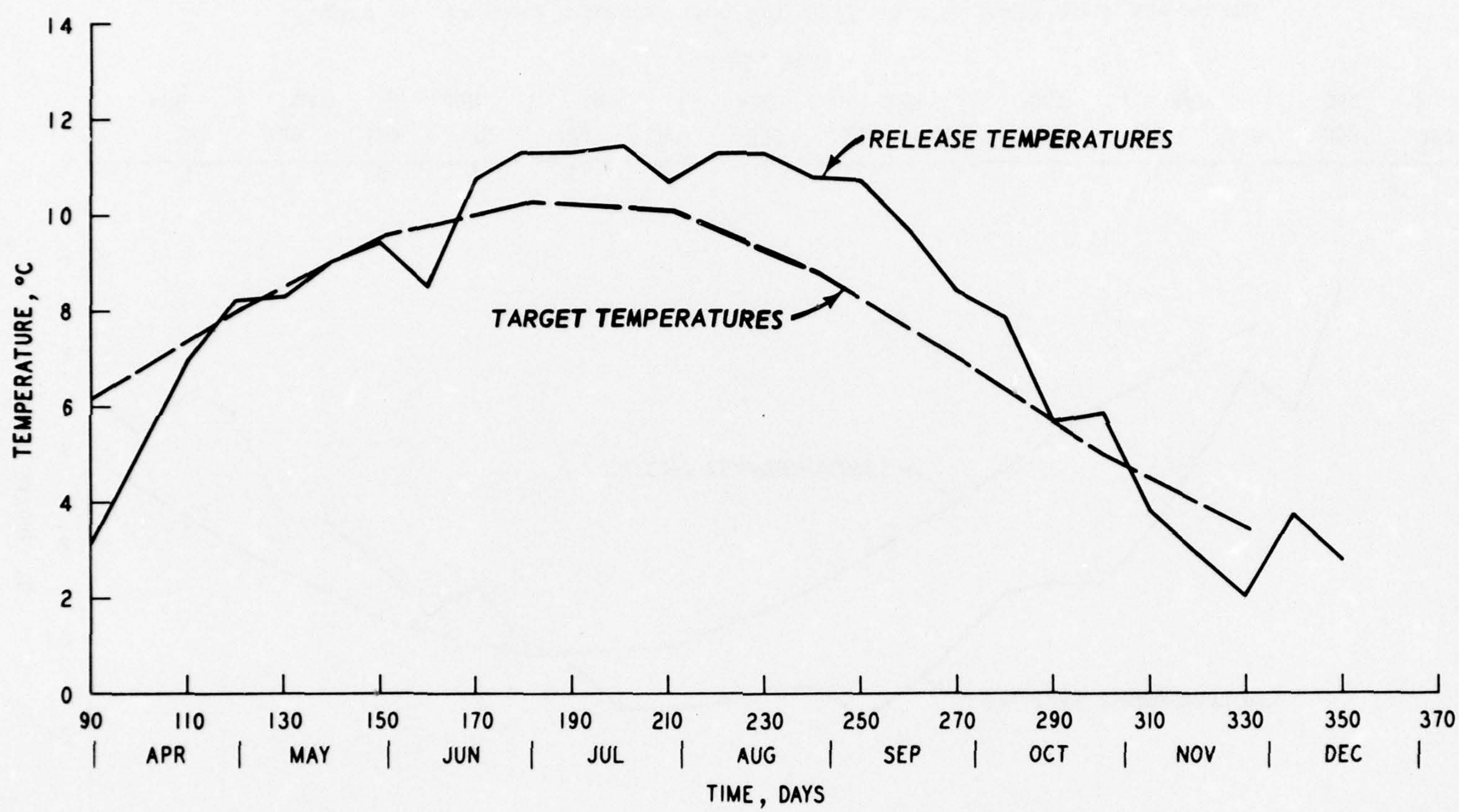

Figure 3. Release temperatures for 1970 at the lower pool elevation

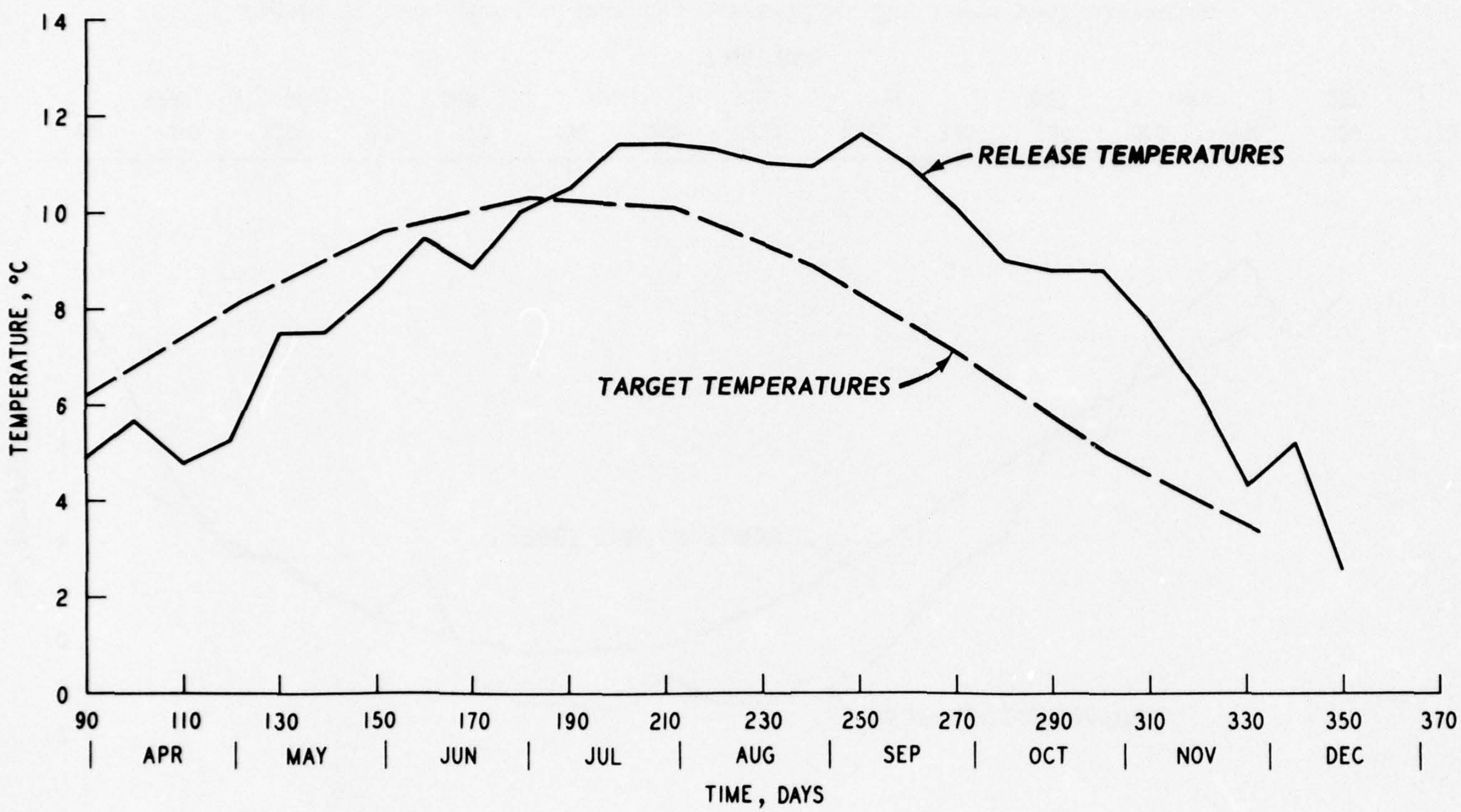

Figure 4. Release temperatures for 1973 at the lower pool elevation

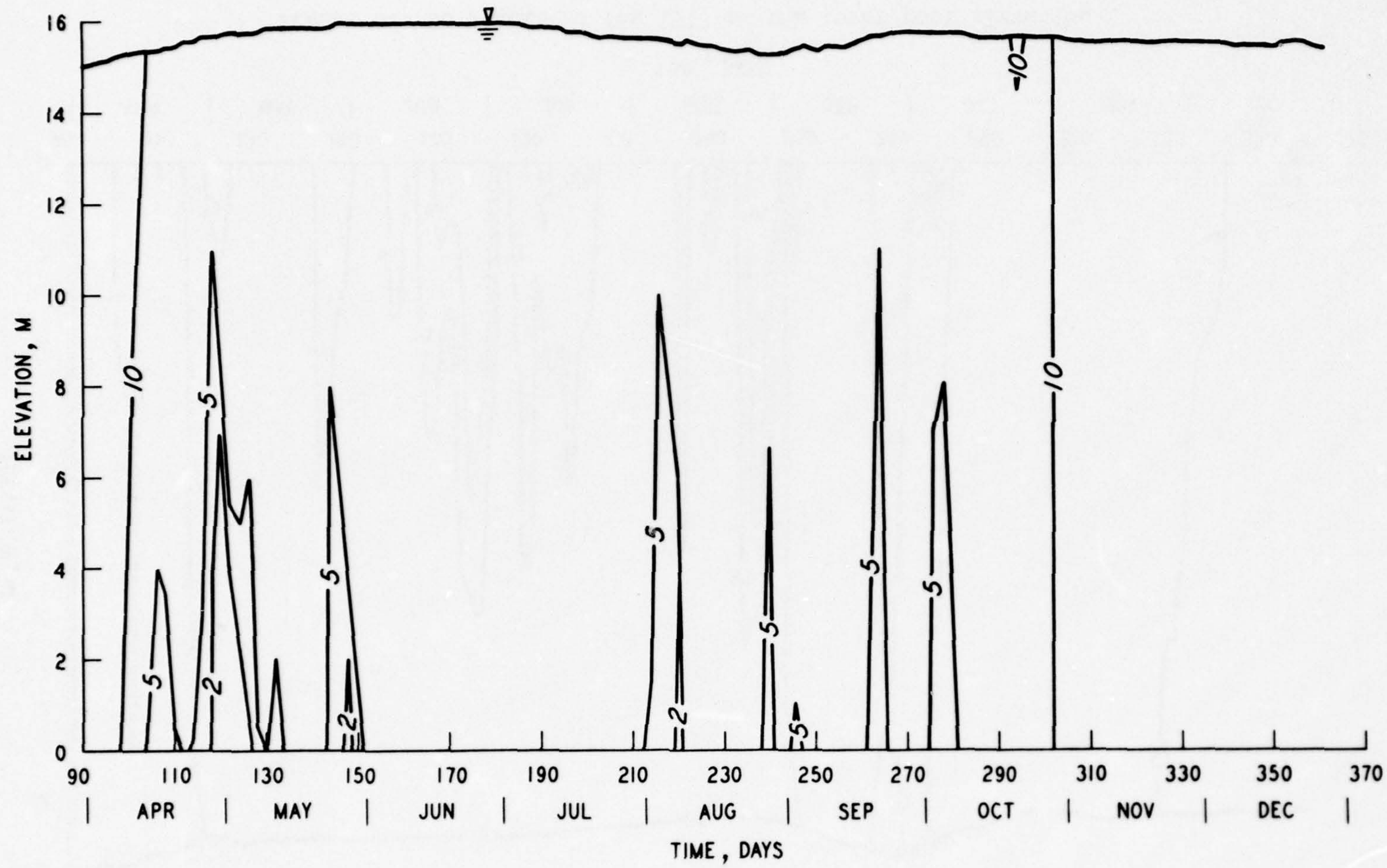

Figure 5. DO isopleths for 1970 at the lower pool elevation

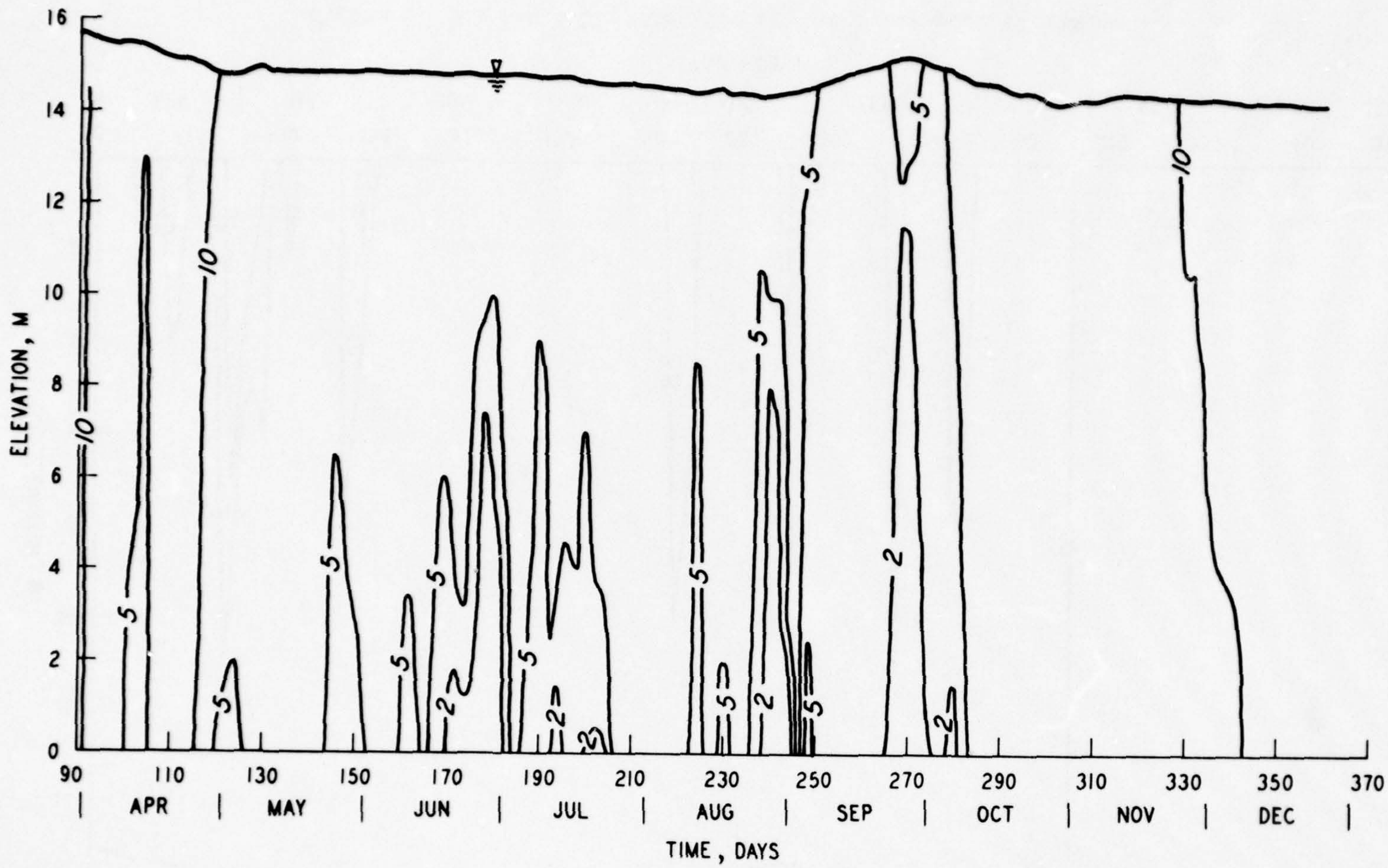

Figure 6. DO isopleths for 1973 at the lower pool elevation

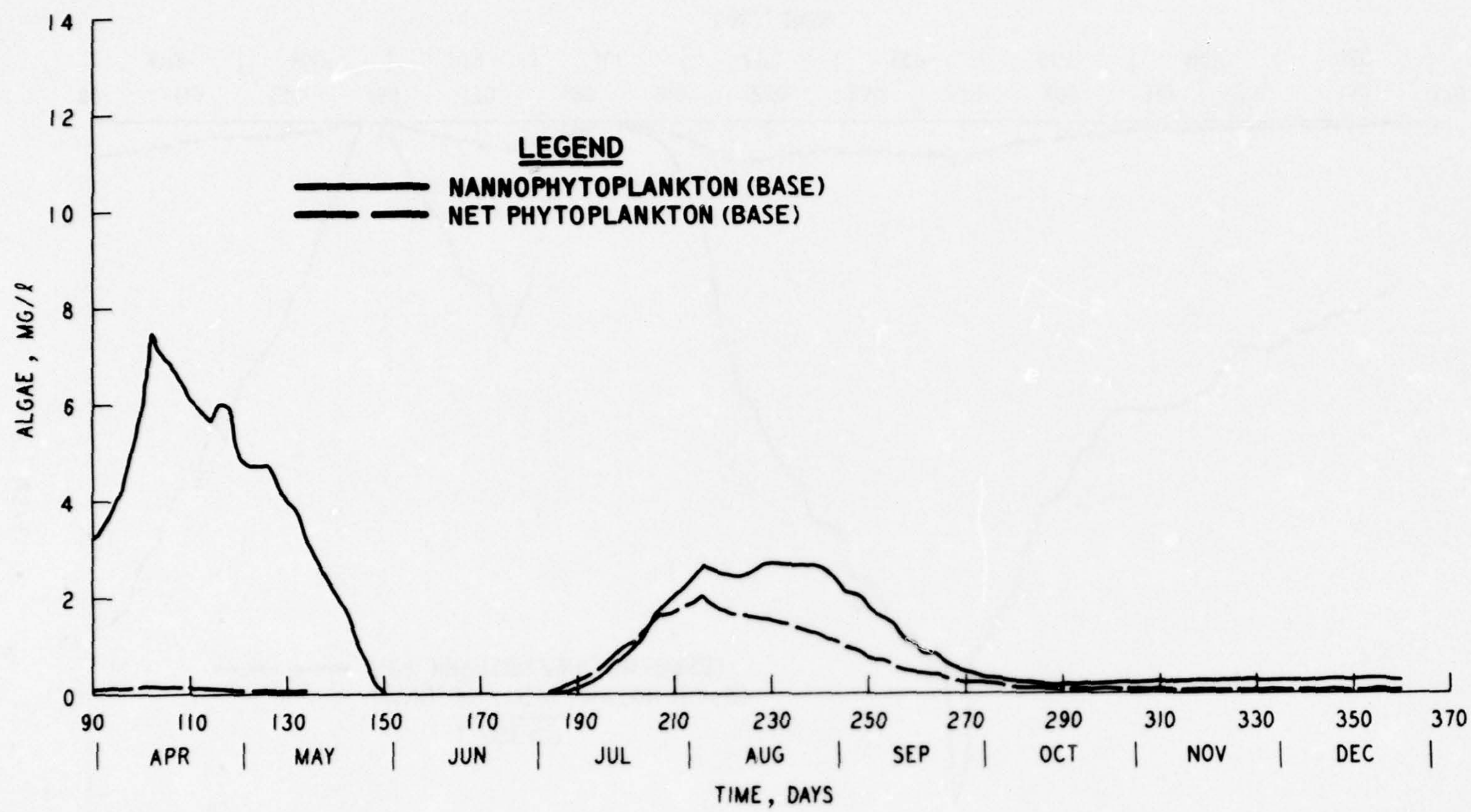

Figure 7. Algae concentrations predicted during 1970 at the lower pool elevation

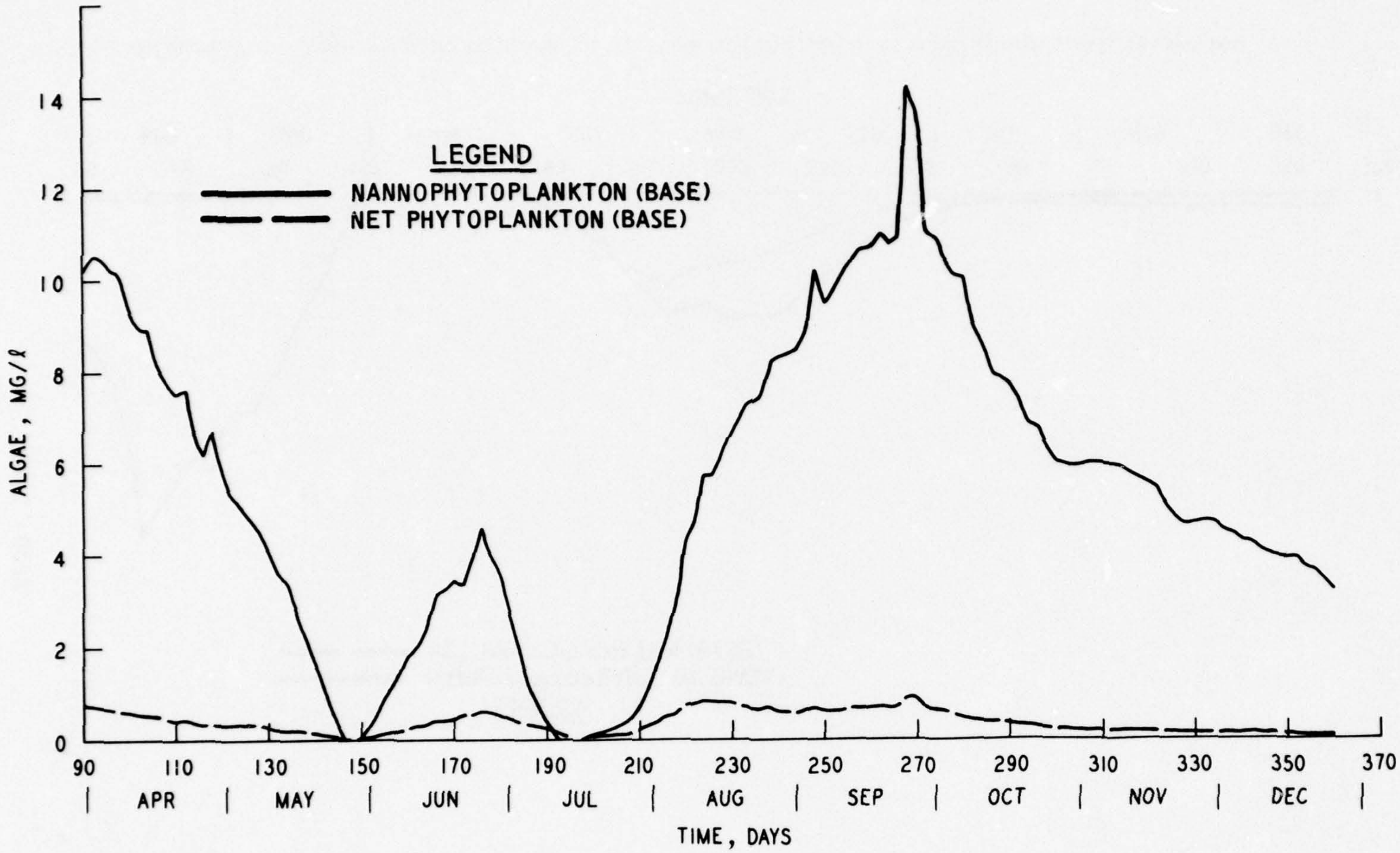

Figure 8. Algae concentrations predicted for 1973 at the lower pool elevation

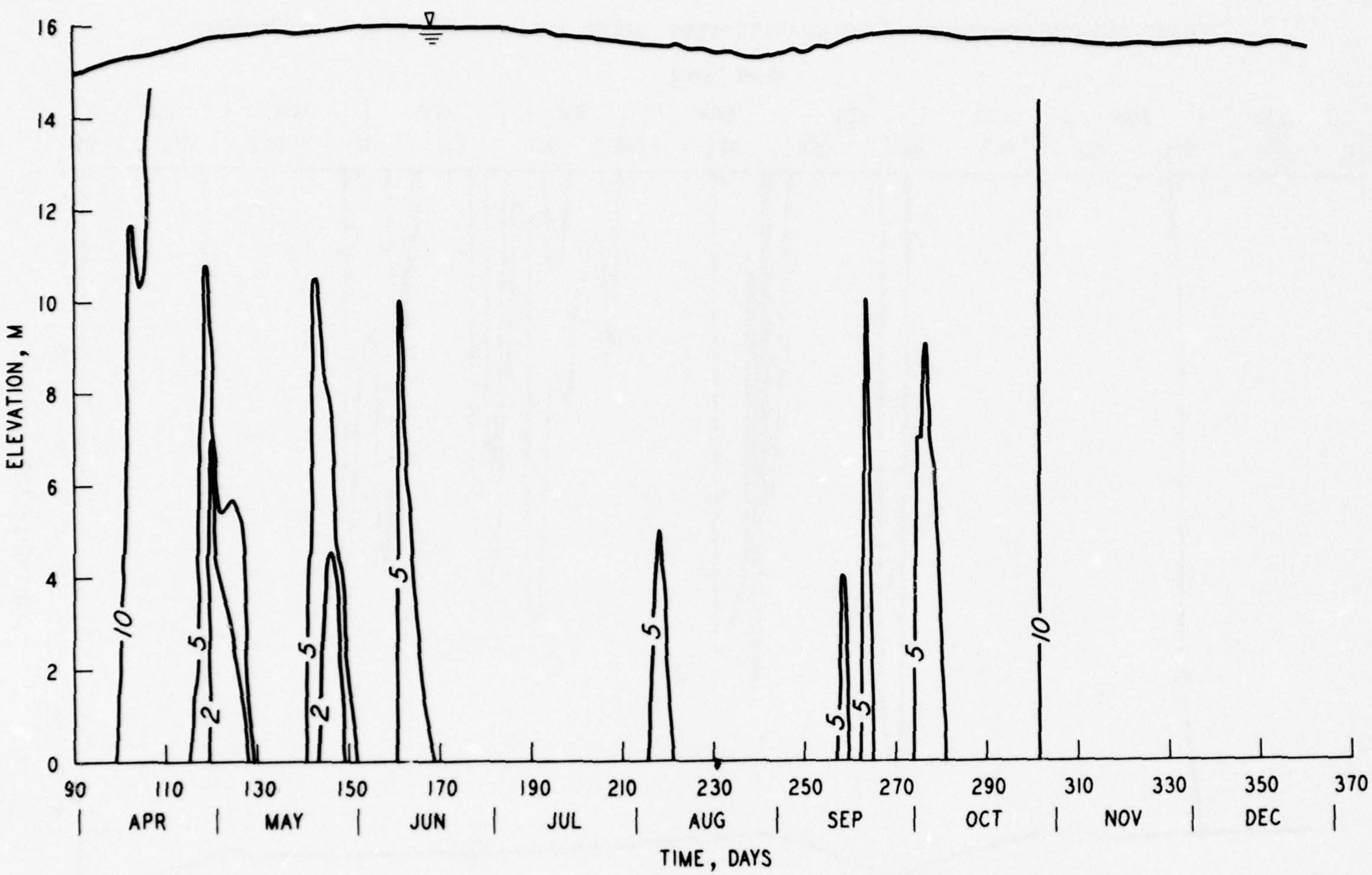

Figure 9. DO isopleths for light half-saturation coefficient during 1970

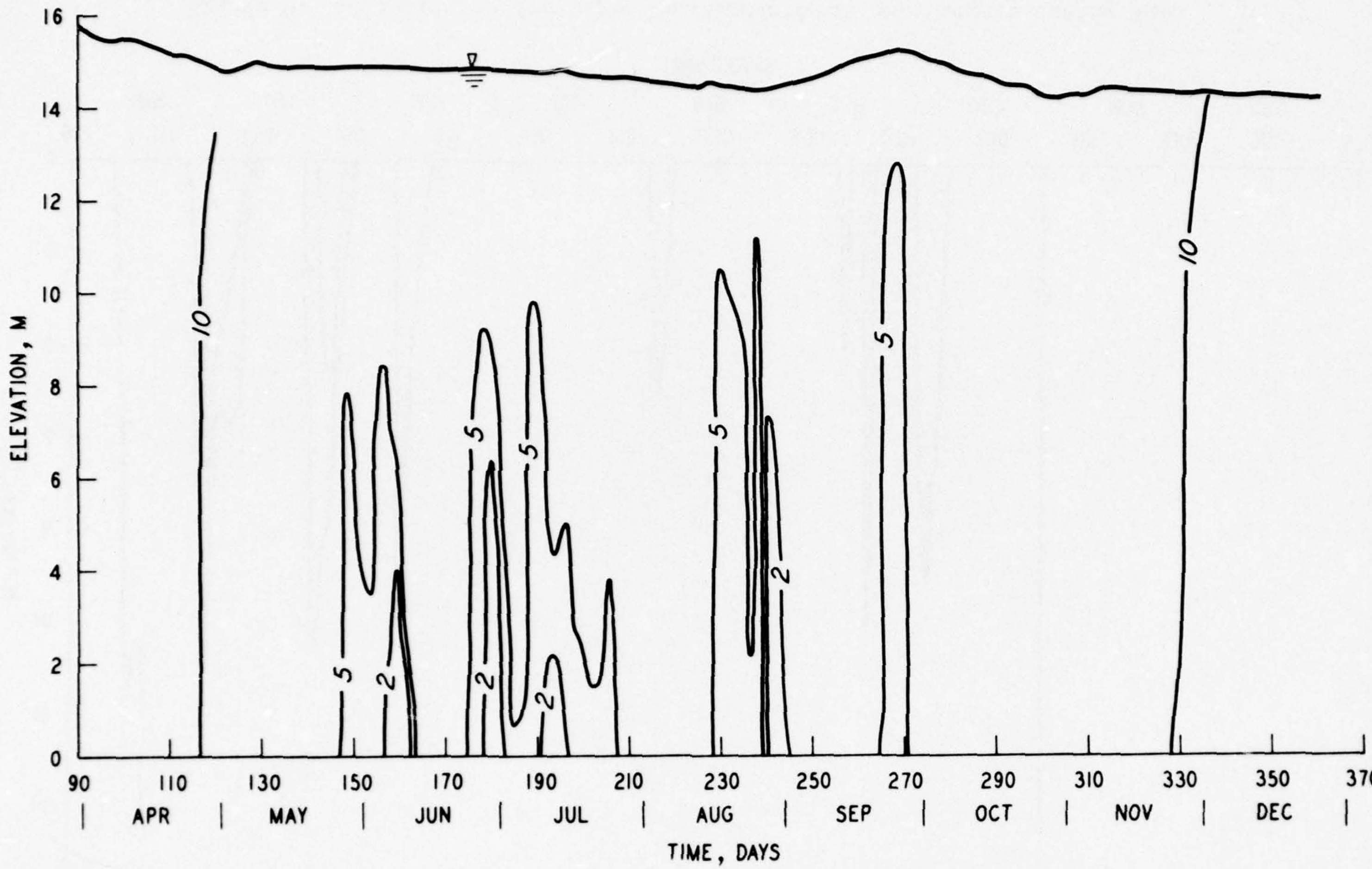

Figure 10. DO isopleths for light half-saturation coefficient during 1973

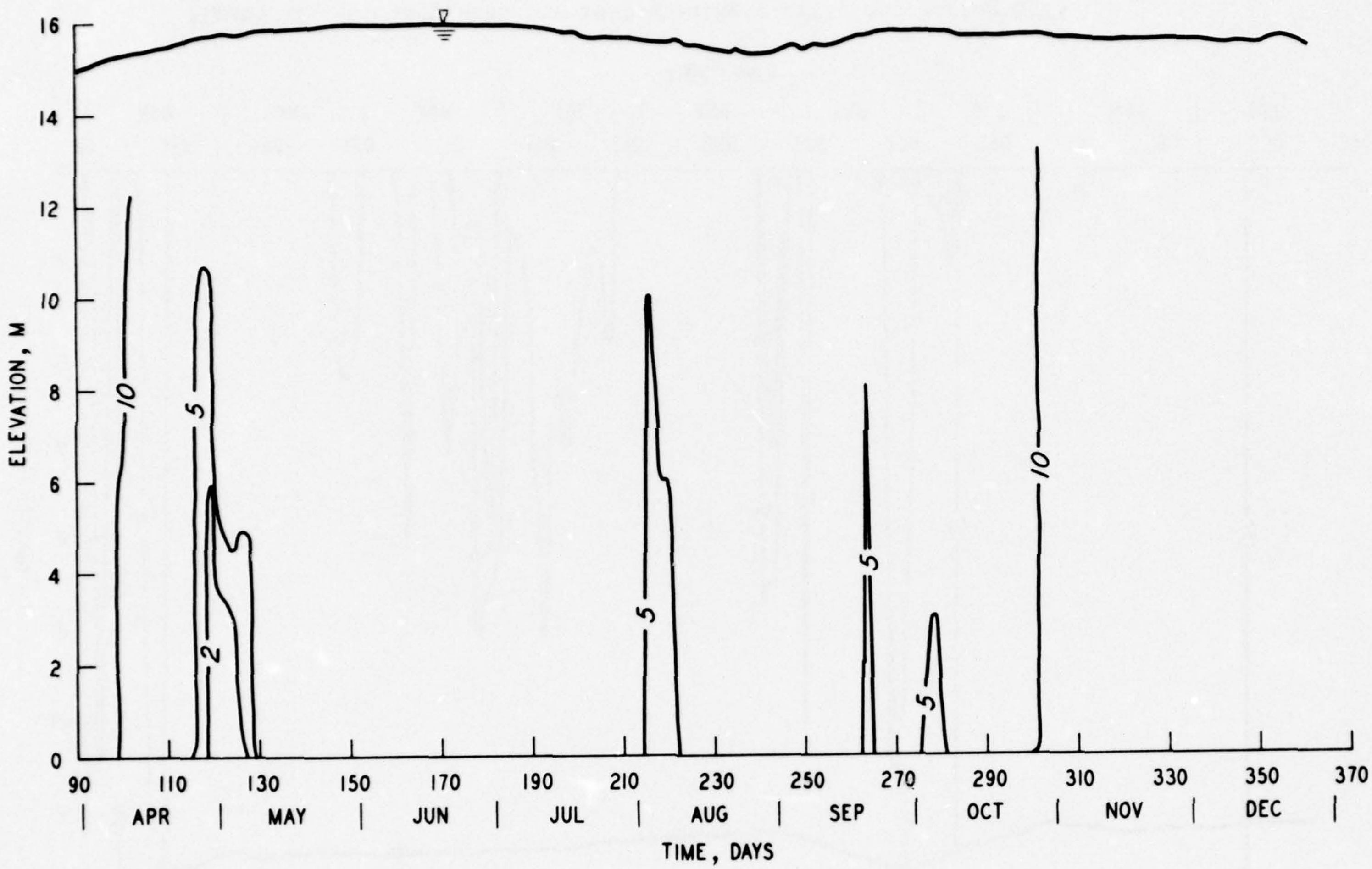

Figure 11. DO isopleths for self-shading coefficient during 1970

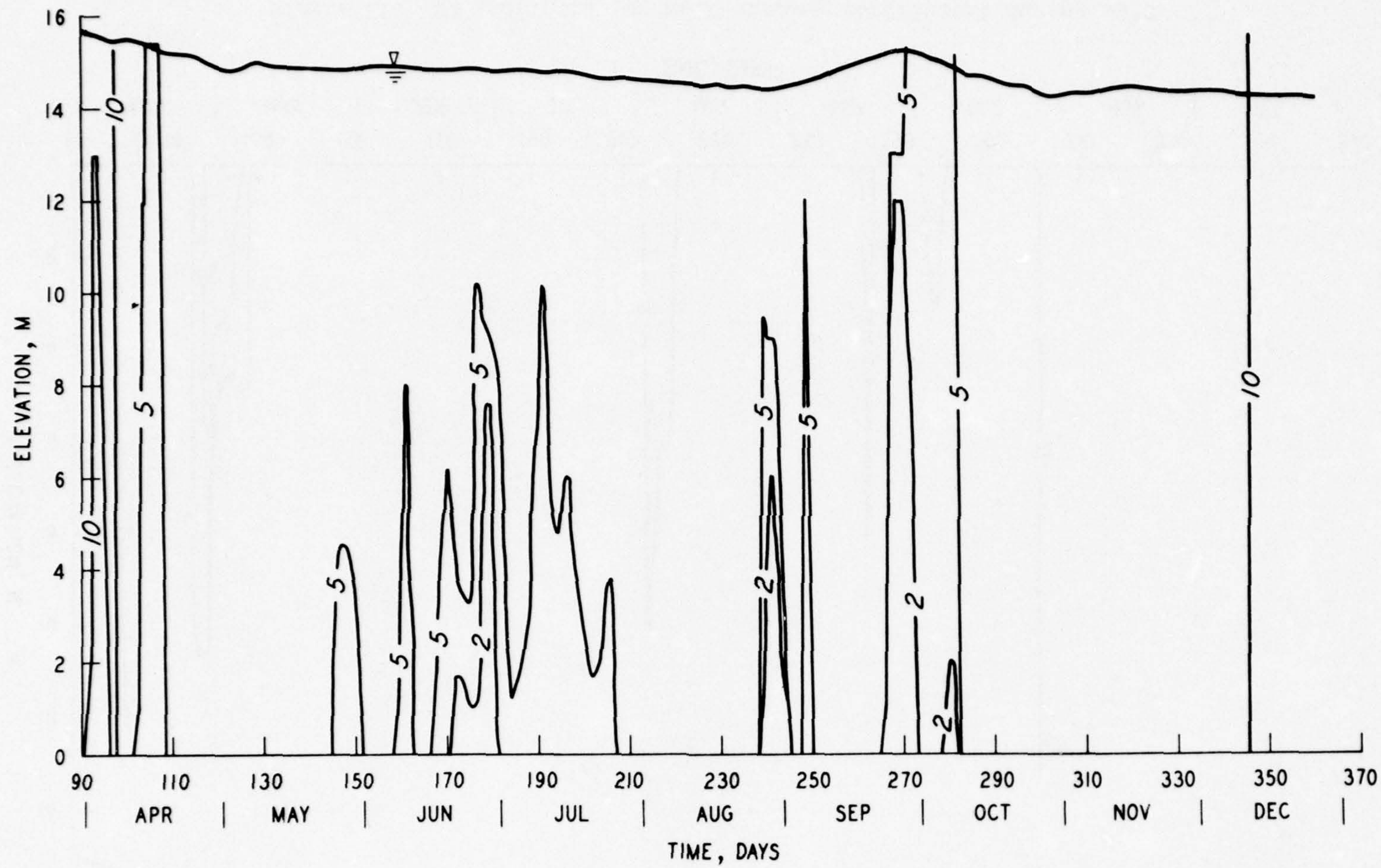

Figure 12. DO isopleths for self-shading coefficient during 1973

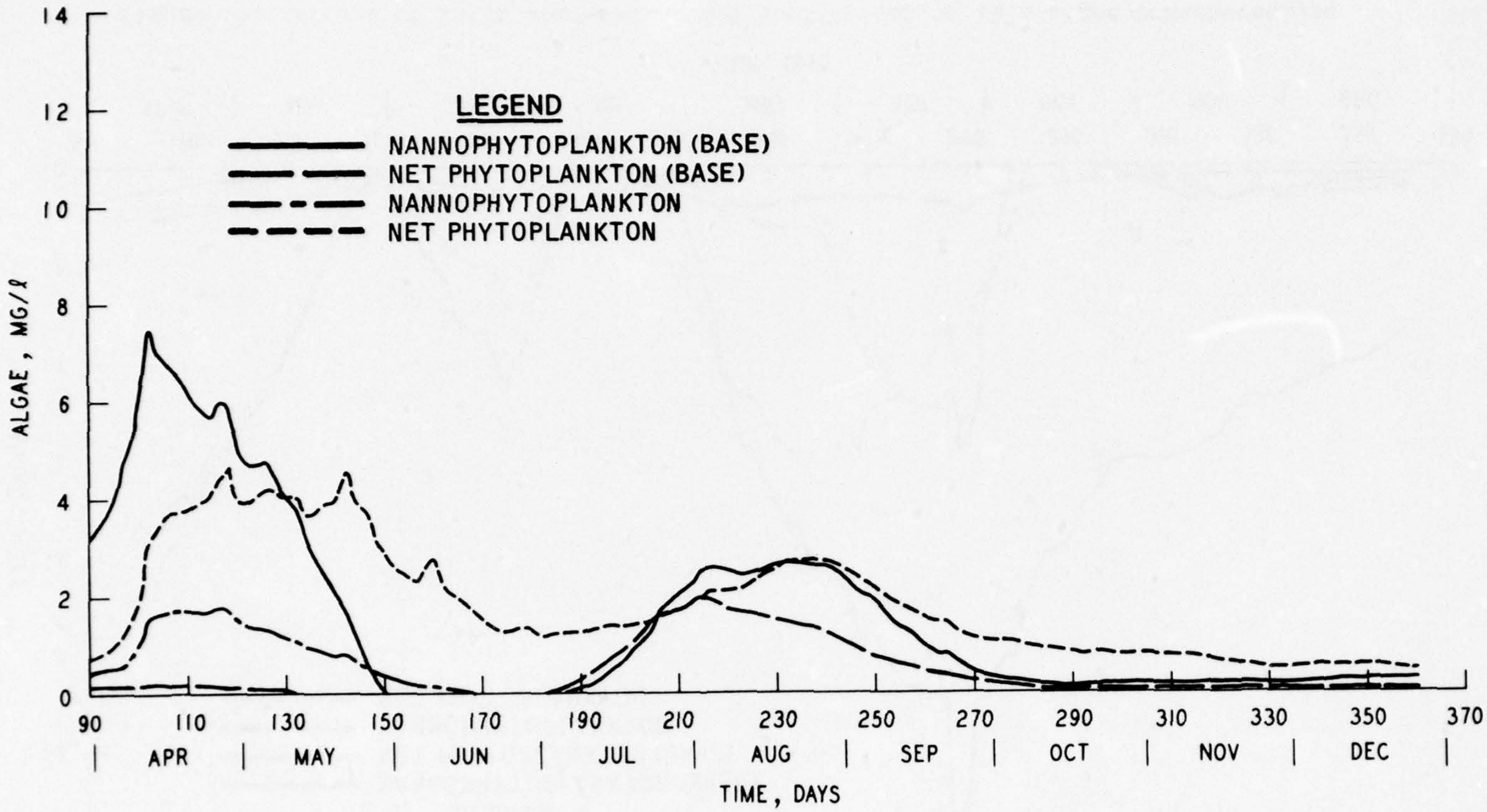

Figure 13. Effect of light half-saturation coefficient on 1970 algae concentrations

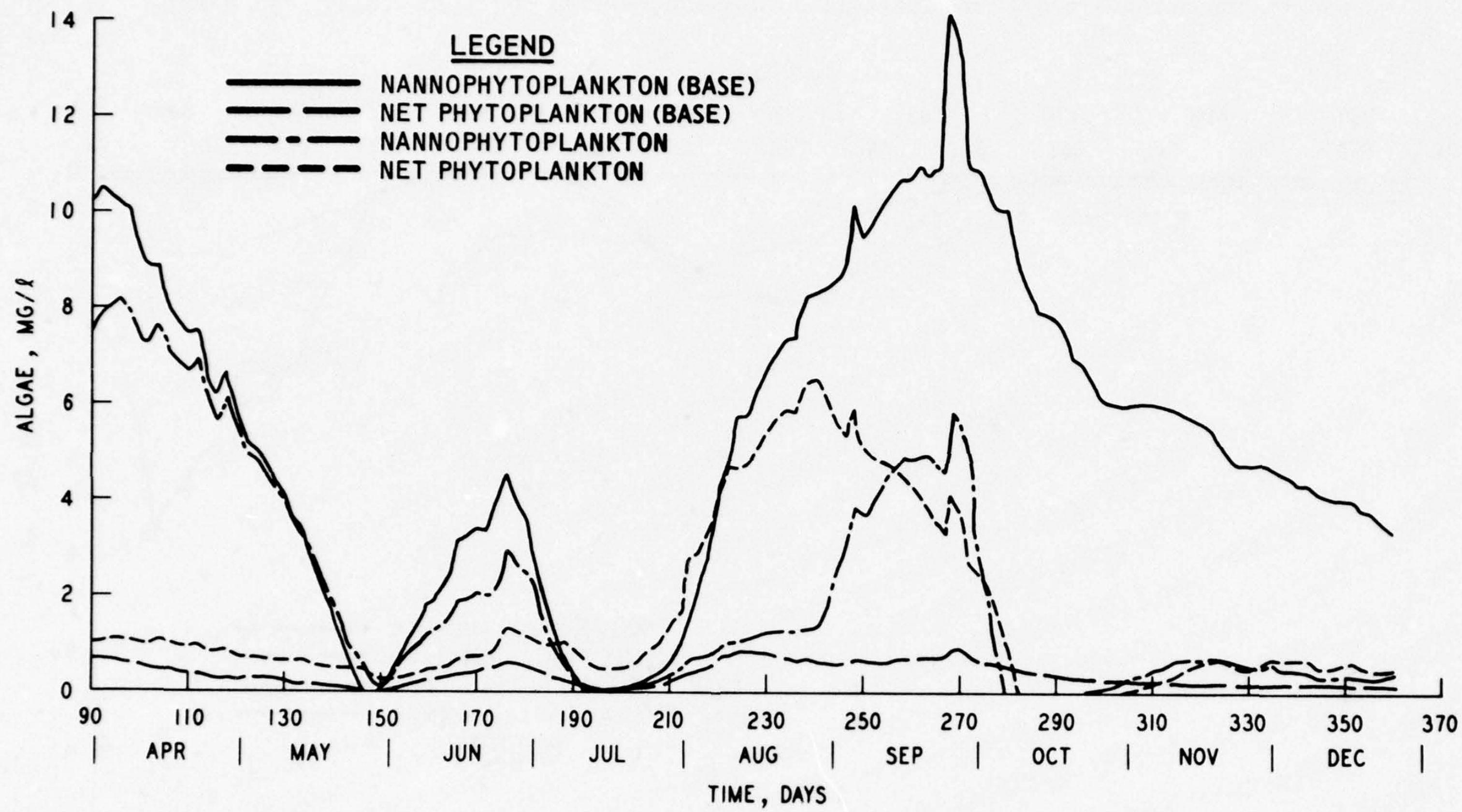

Figure 14. Effect of light half-saturation coefficient on 1973 algae concentrations

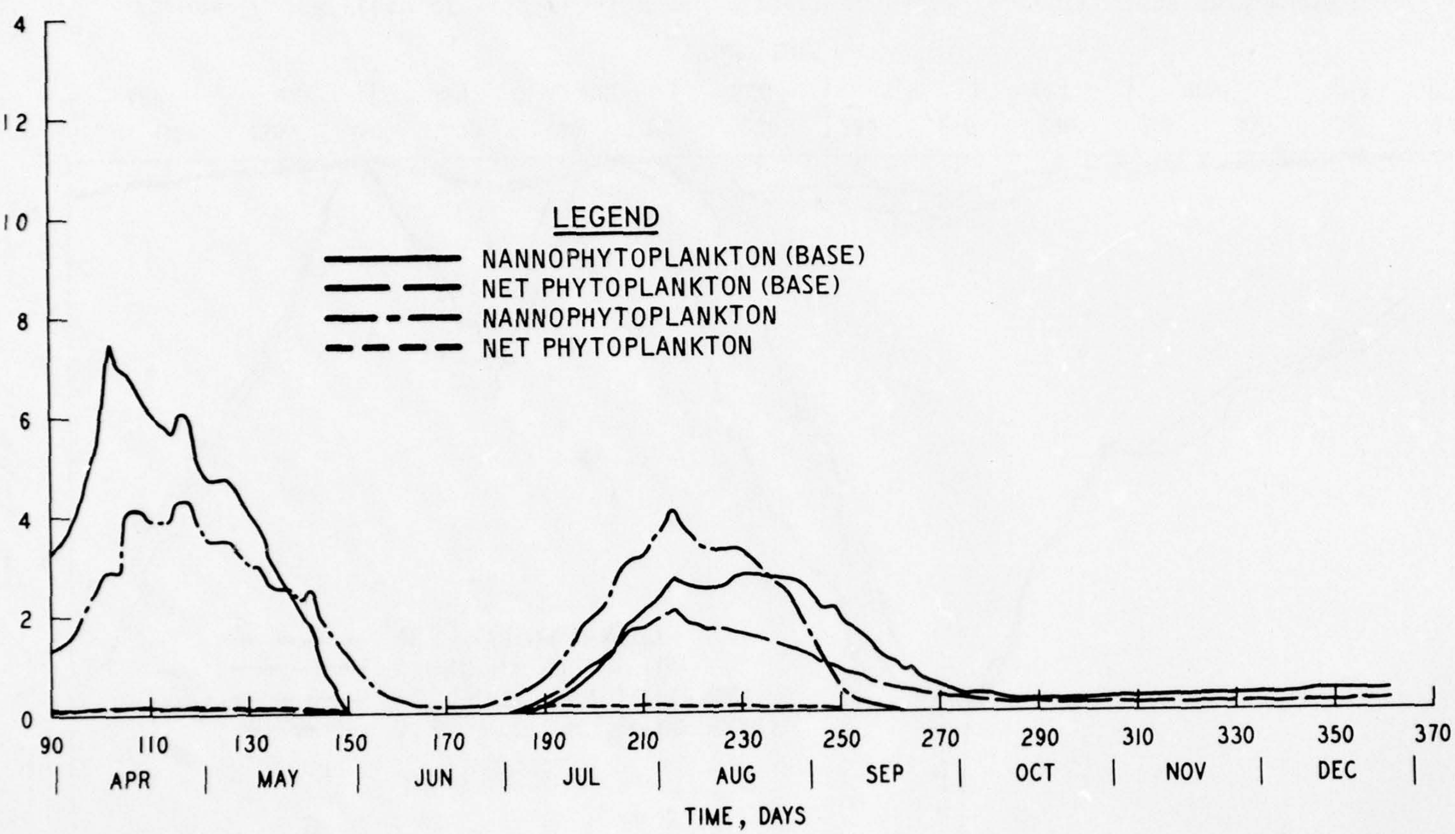

Figure 15. Effects of self-shading coefficient on algae concentrations during 1970

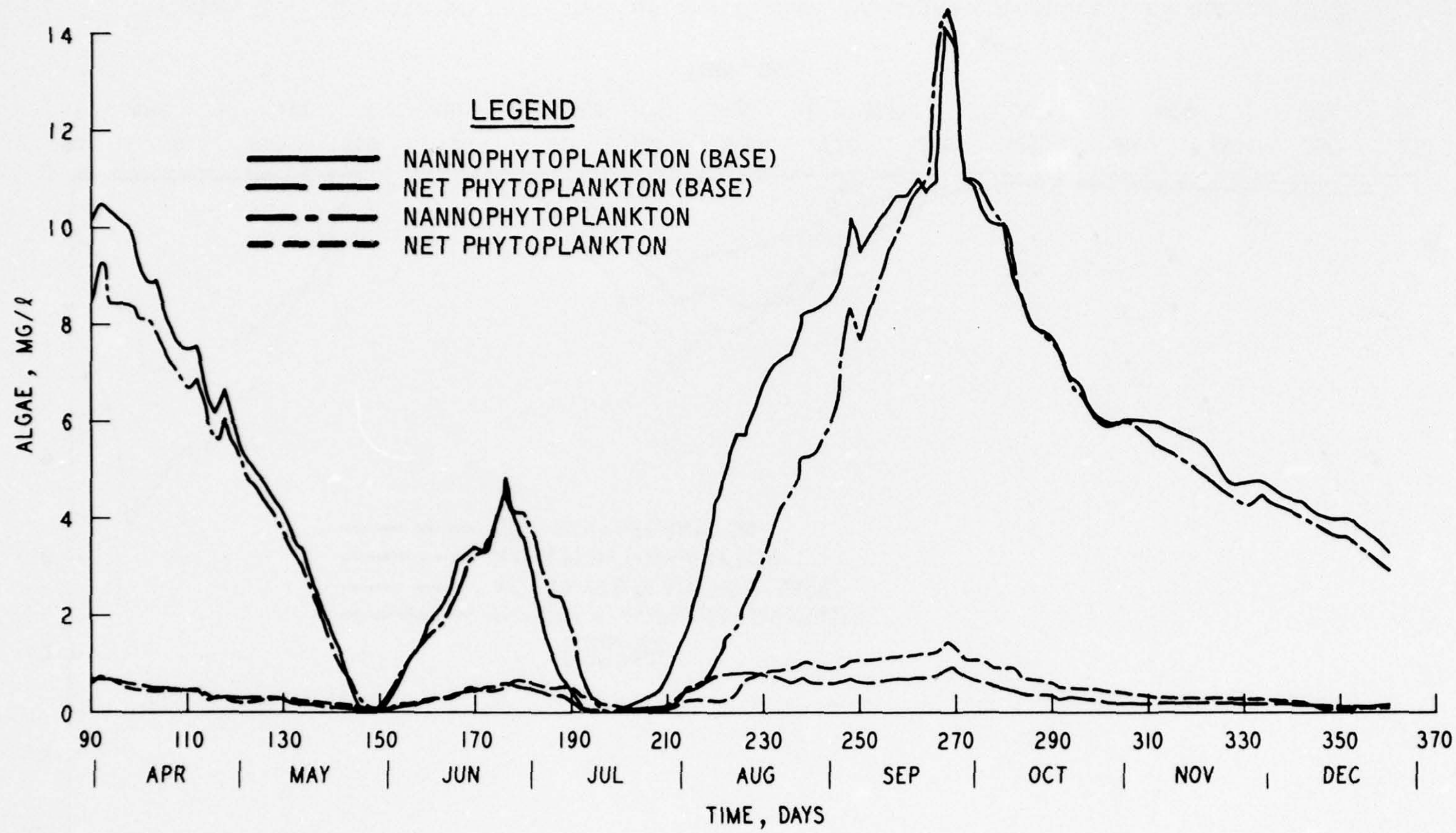

Figure 16. Effects of self-shading coefficient on algae concentrations during 1973

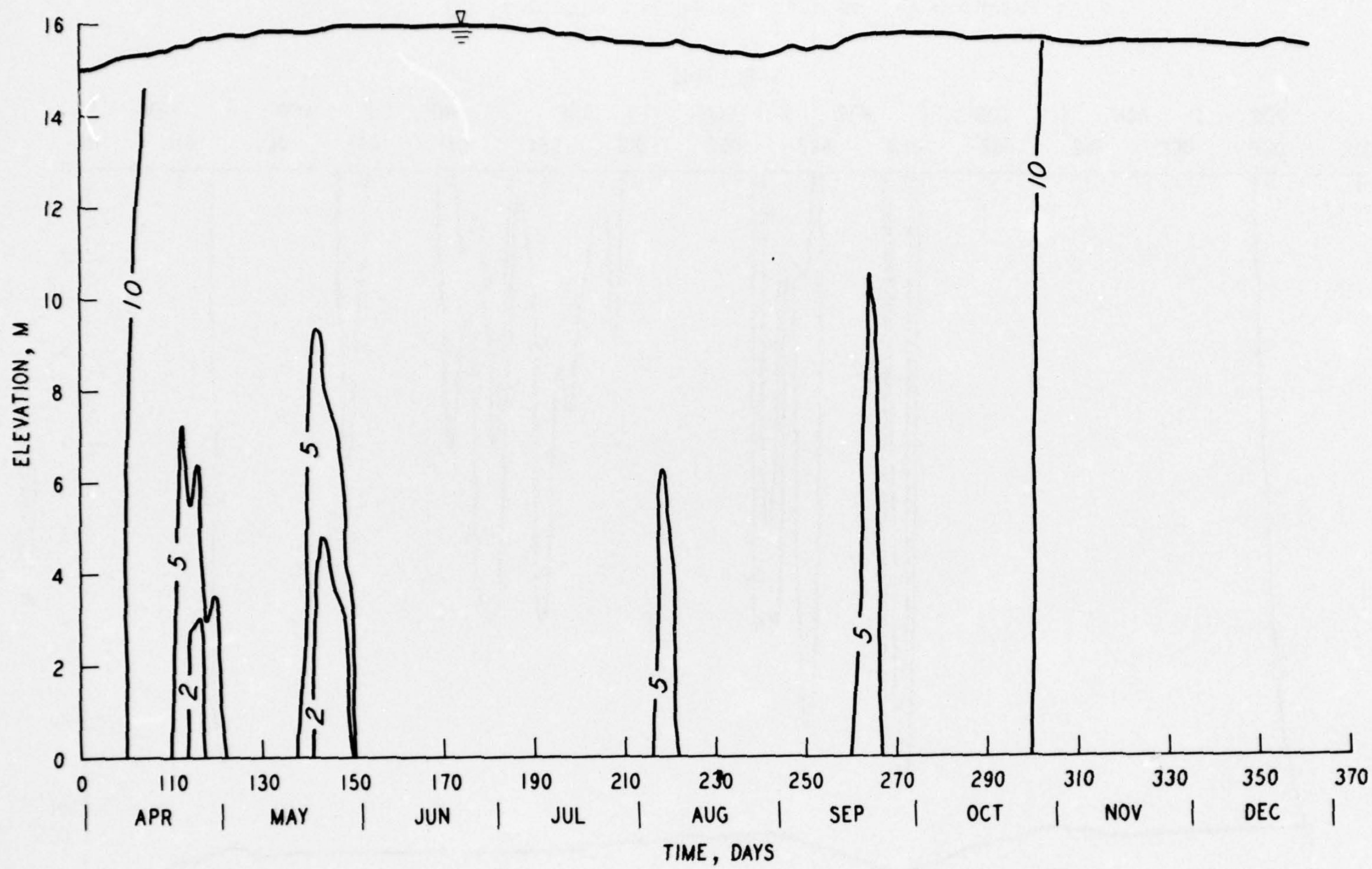

Figure 17. DO isopleths for Secchi disk at 1.0 m during 1970

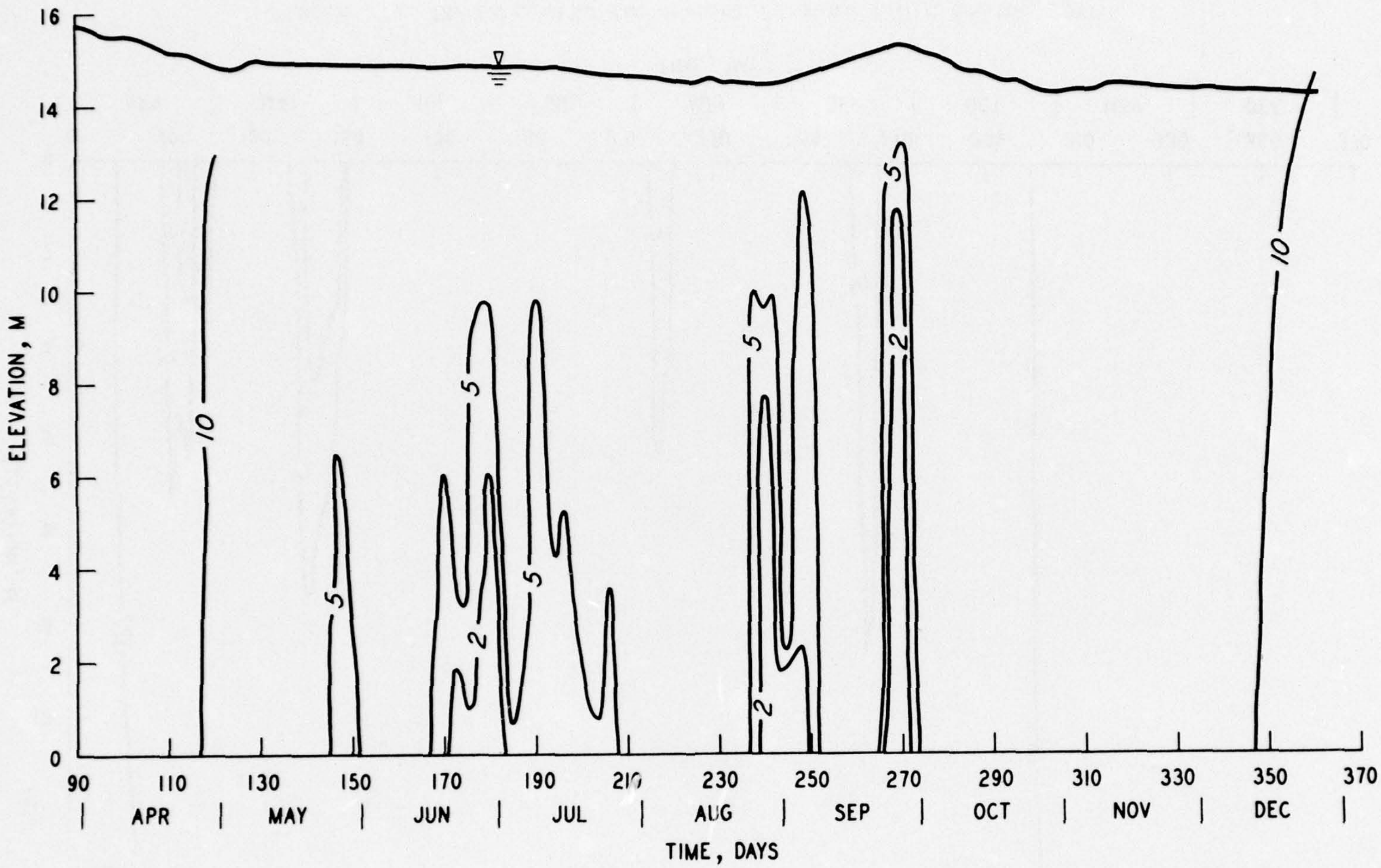

Figure 18. DO isopleths for Secchi disk at 1.0 m during 1973

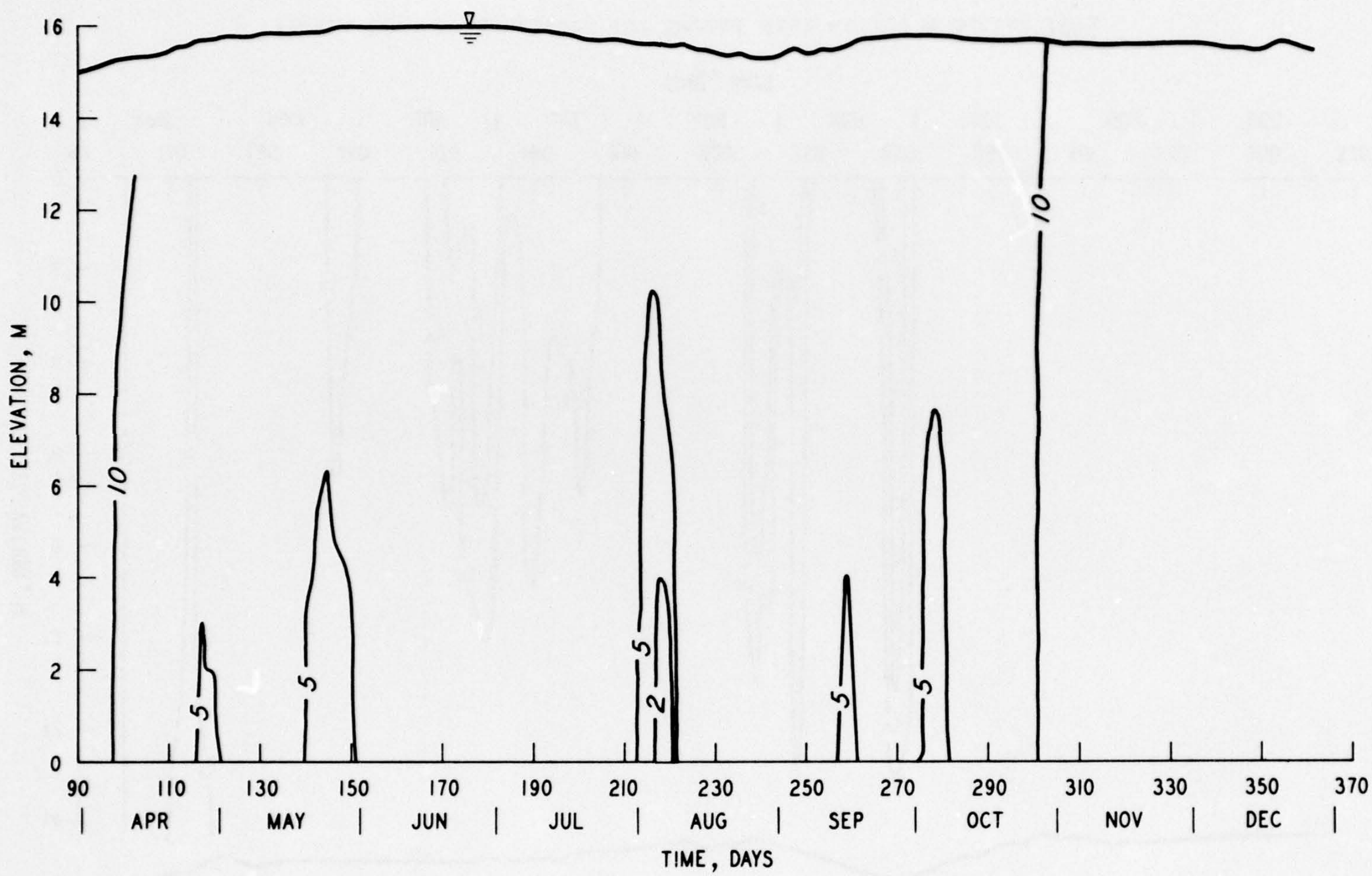

Figure 19. DO isopleths for Secchi disk at 3.0 m during 1970

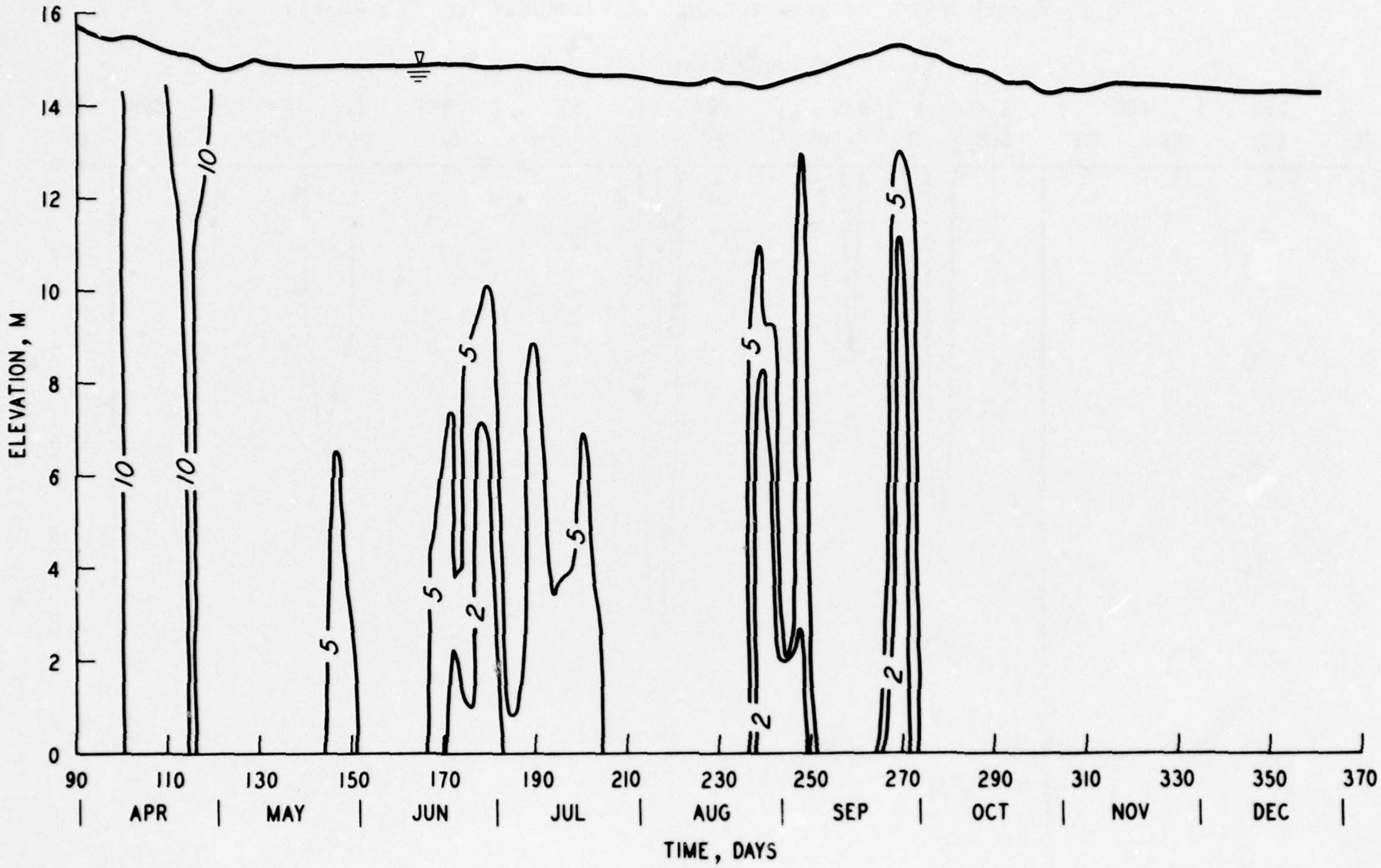

Figure 20. DO isopleths for Secchi disk at 3.0 m during 1973

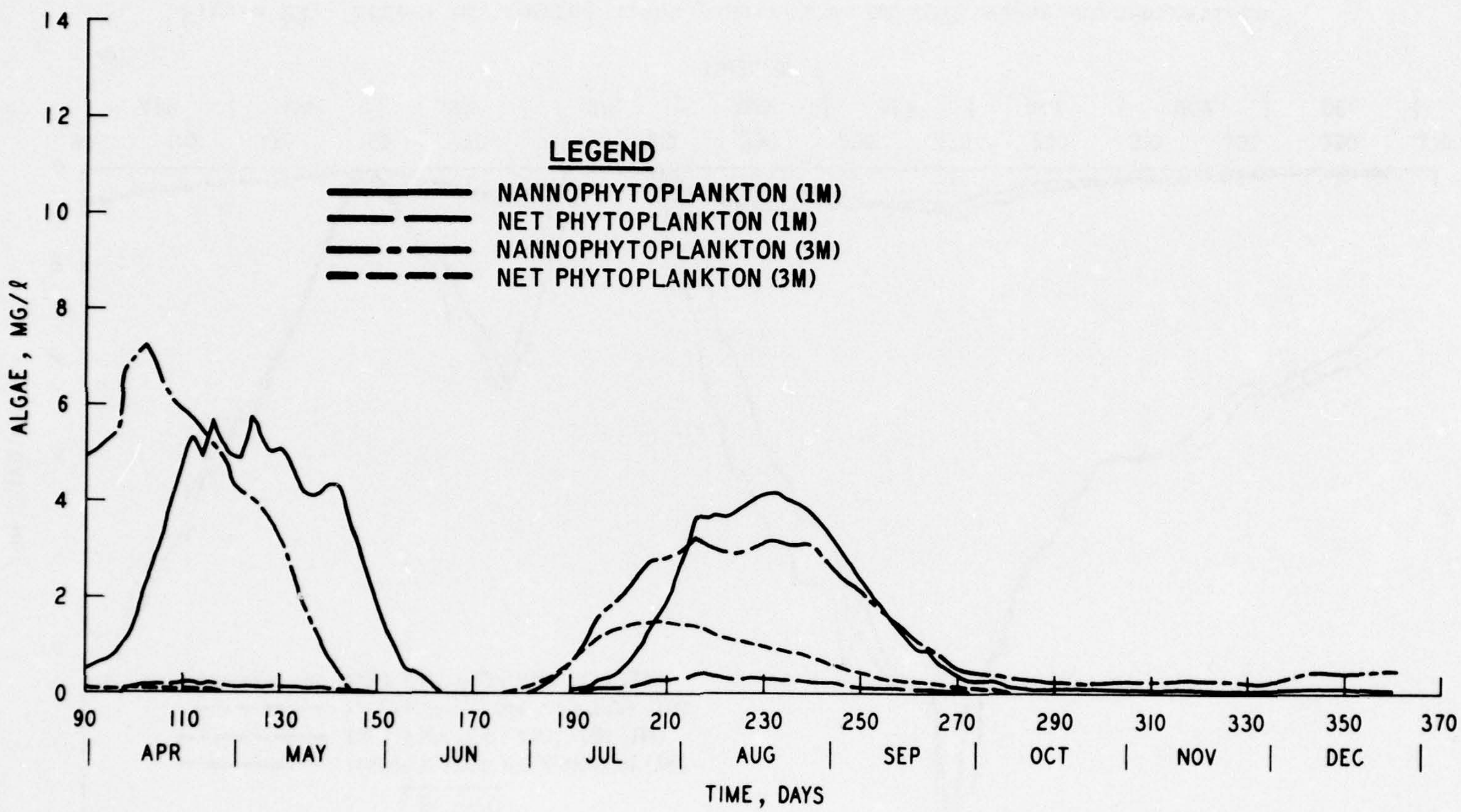

Figure 21. Effect of varying light penetration on 1970 algae concentrations

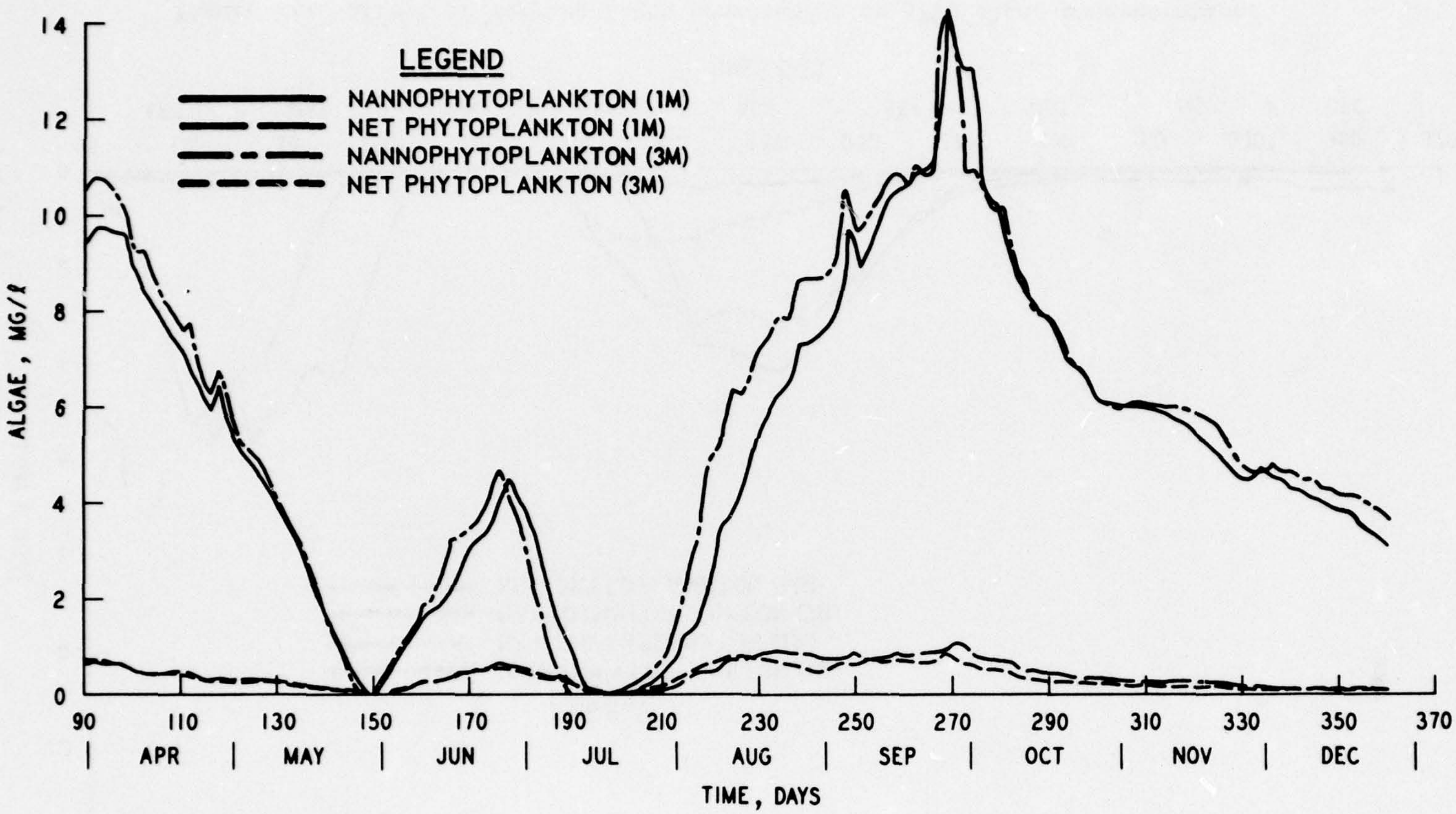

Figure 22. Effect of varying light penetration on 1973 algae concentrations

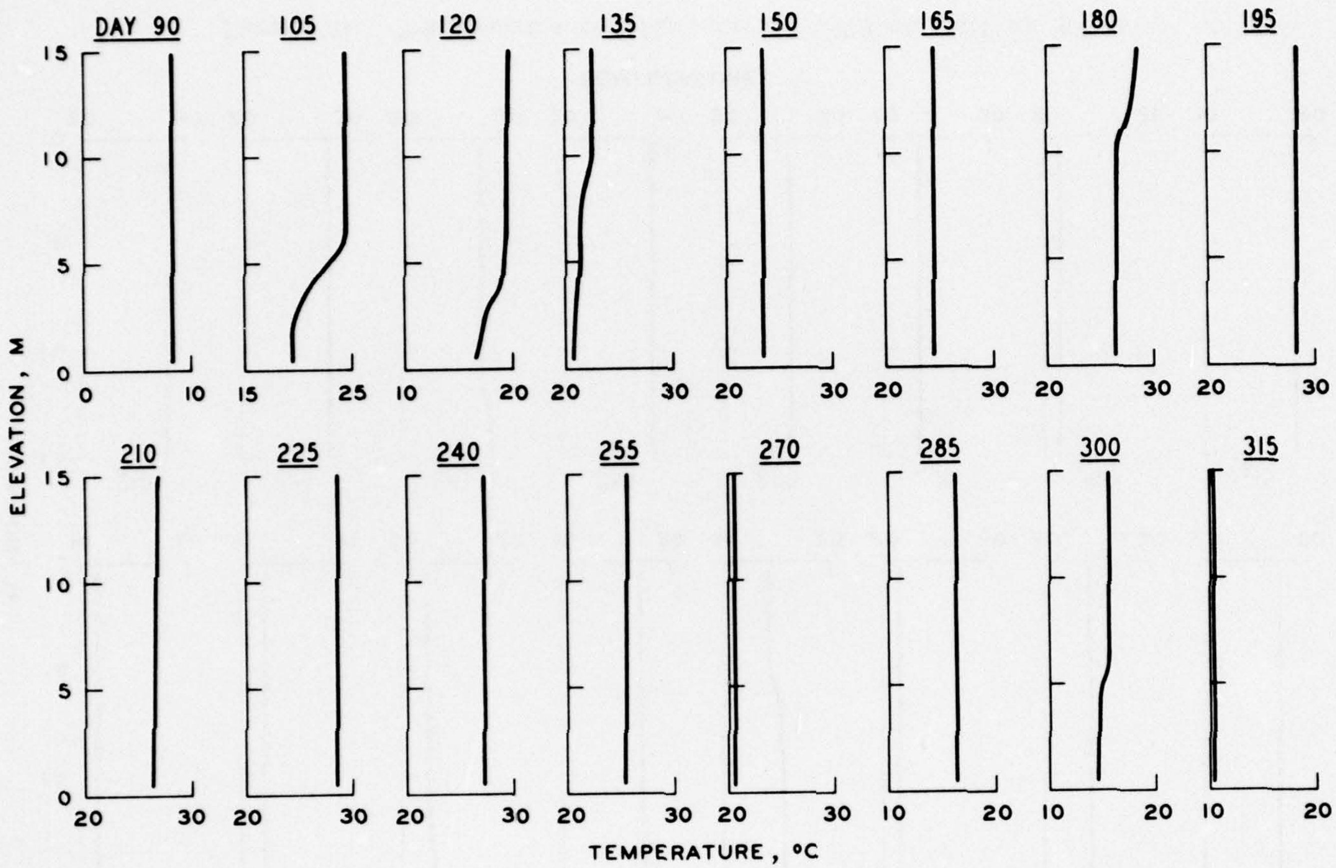

Figure 23. Temperature profiles during 1970 at pool el 308 m

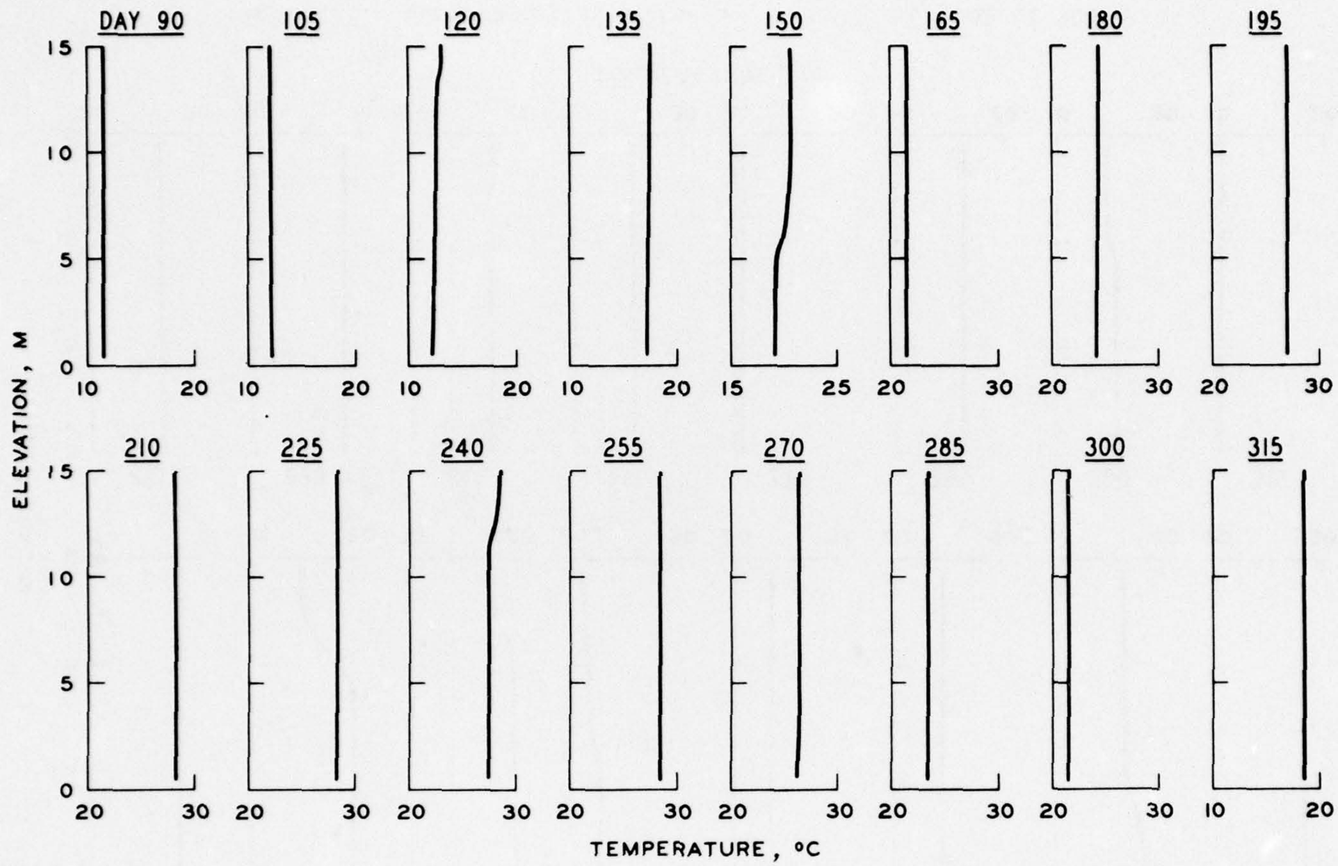

Figure 24. Temperature profiles during 1973 at pool el 308 m

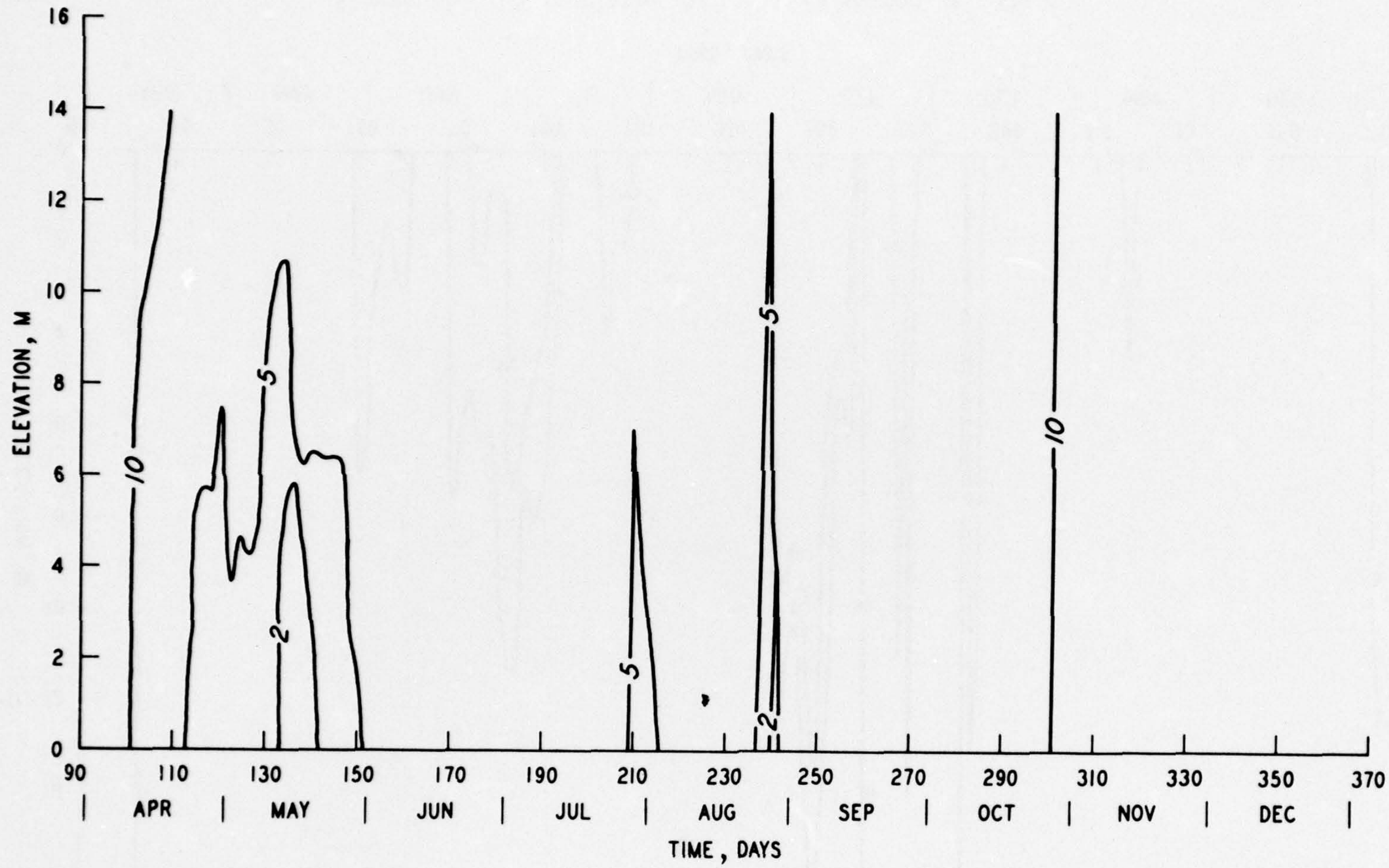

Figure 25. DO isopleths during 1970 at pool el 308 m

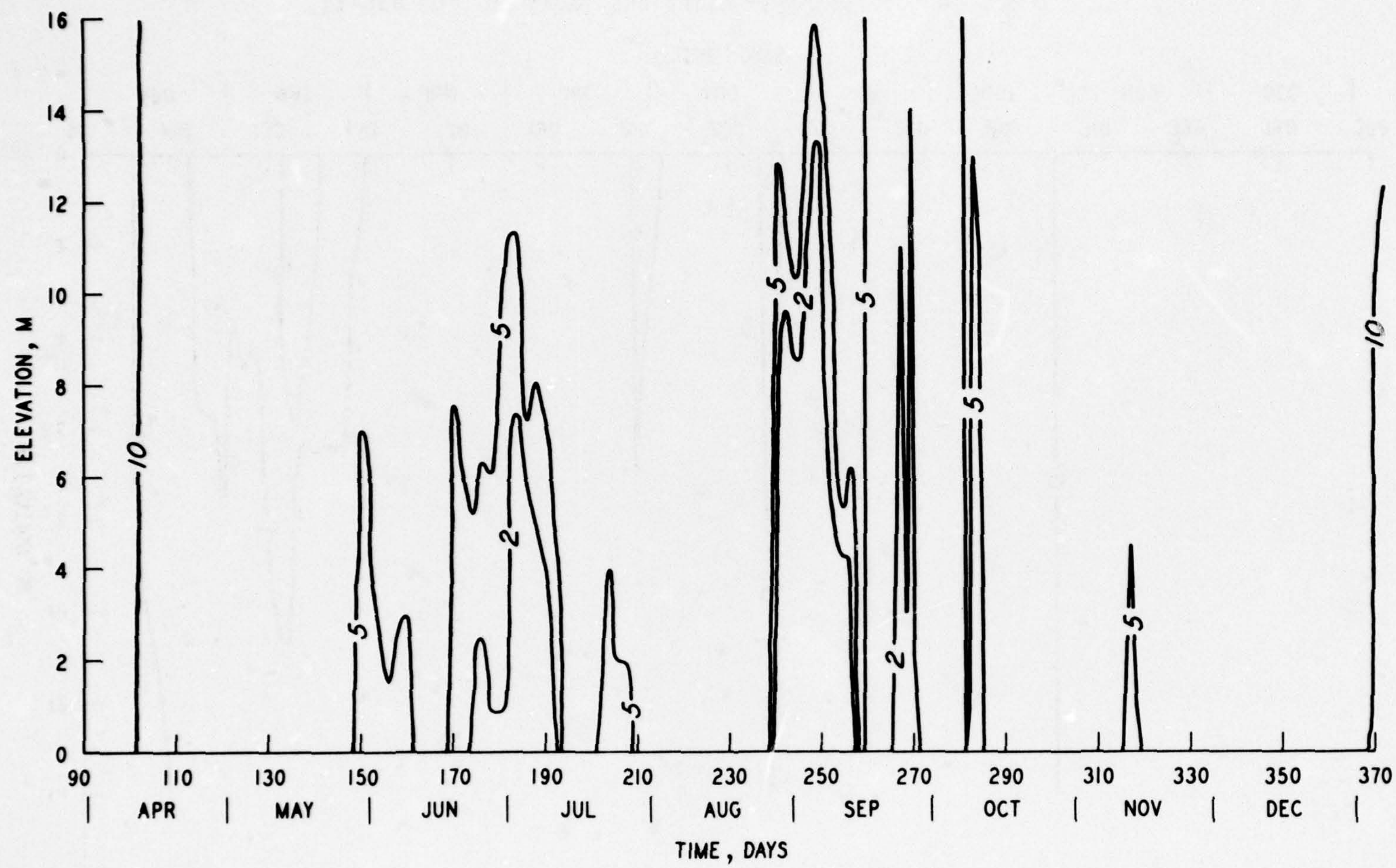

Figure 26. DO isopleths during 1973 at pool el 308 m

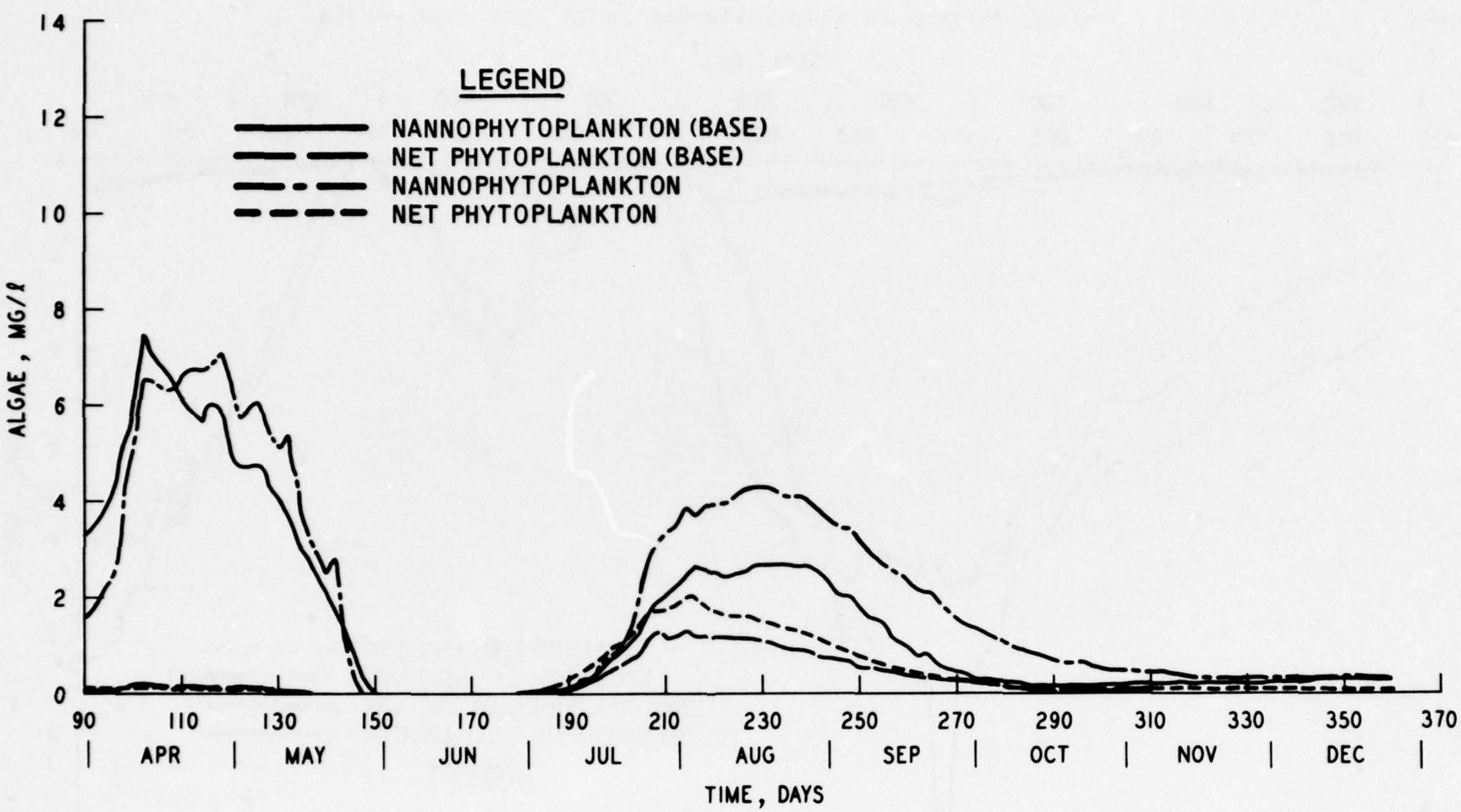

Figure 27. 1970 algae concentrations at pool el 308 m

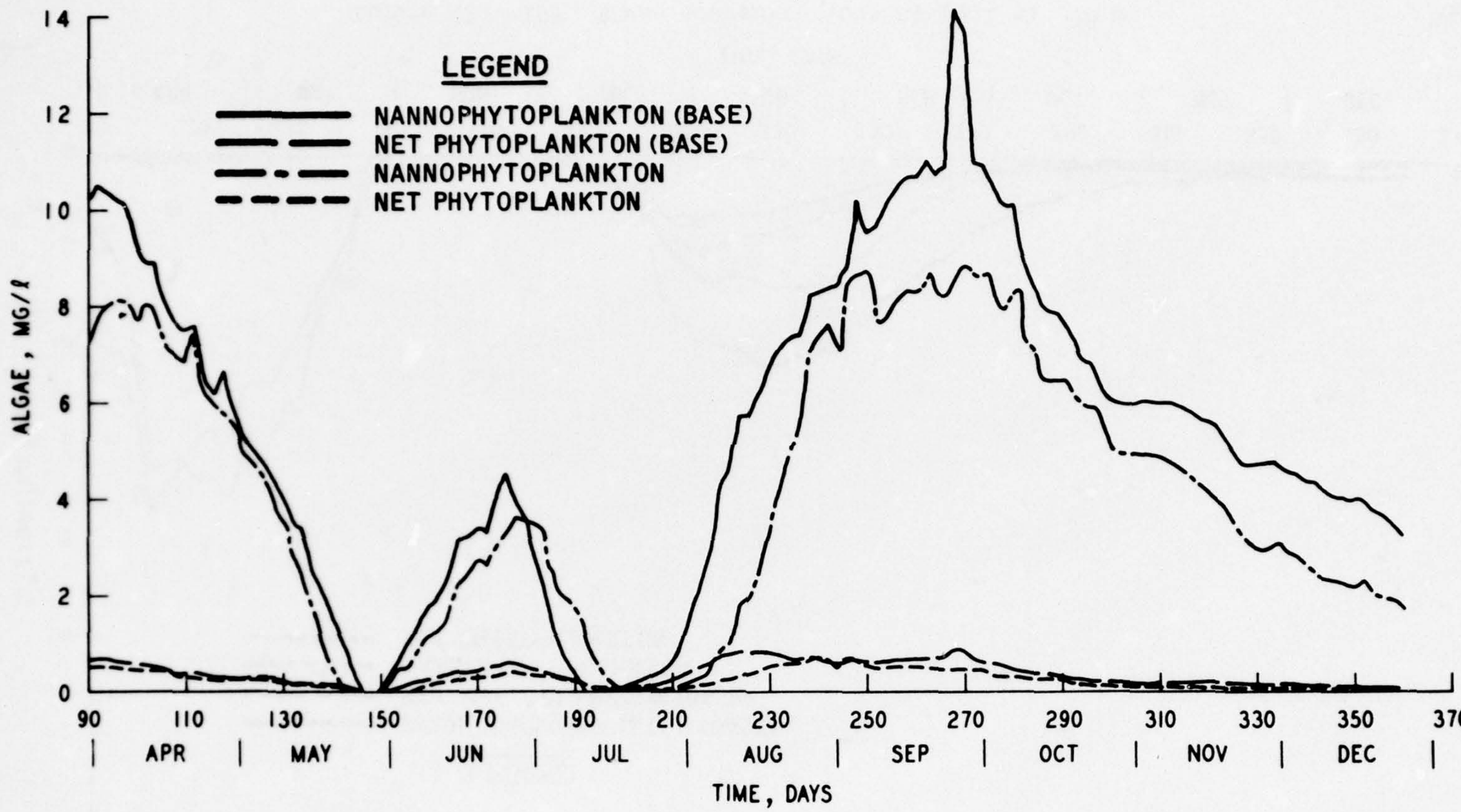

Figure 28. 1973 algae concentrations at pool el 308 m

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Prepared for U. S. Army Engineer District, Tulsa, Tulsa, Oklahoma.

Includes bibliography.

1. Arcadia Lake, Okla. 2. Computerized simulation. 3. Mathematical models. 4. Reservoirs. 5. Water quality. I. Eley, Rex L., joint author. II. Ford, Dennis E., joint author. III. Hall, Ross W., joint author. IV. Robey, Donald L., joint author. V. U. S. Army Engineer District, Tulsa. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report Y-77-3)

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